Hadronic final states in high-p_T QCD with the CMS detector

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(On behalf of CMS collaboration)

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Chicago

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Outline

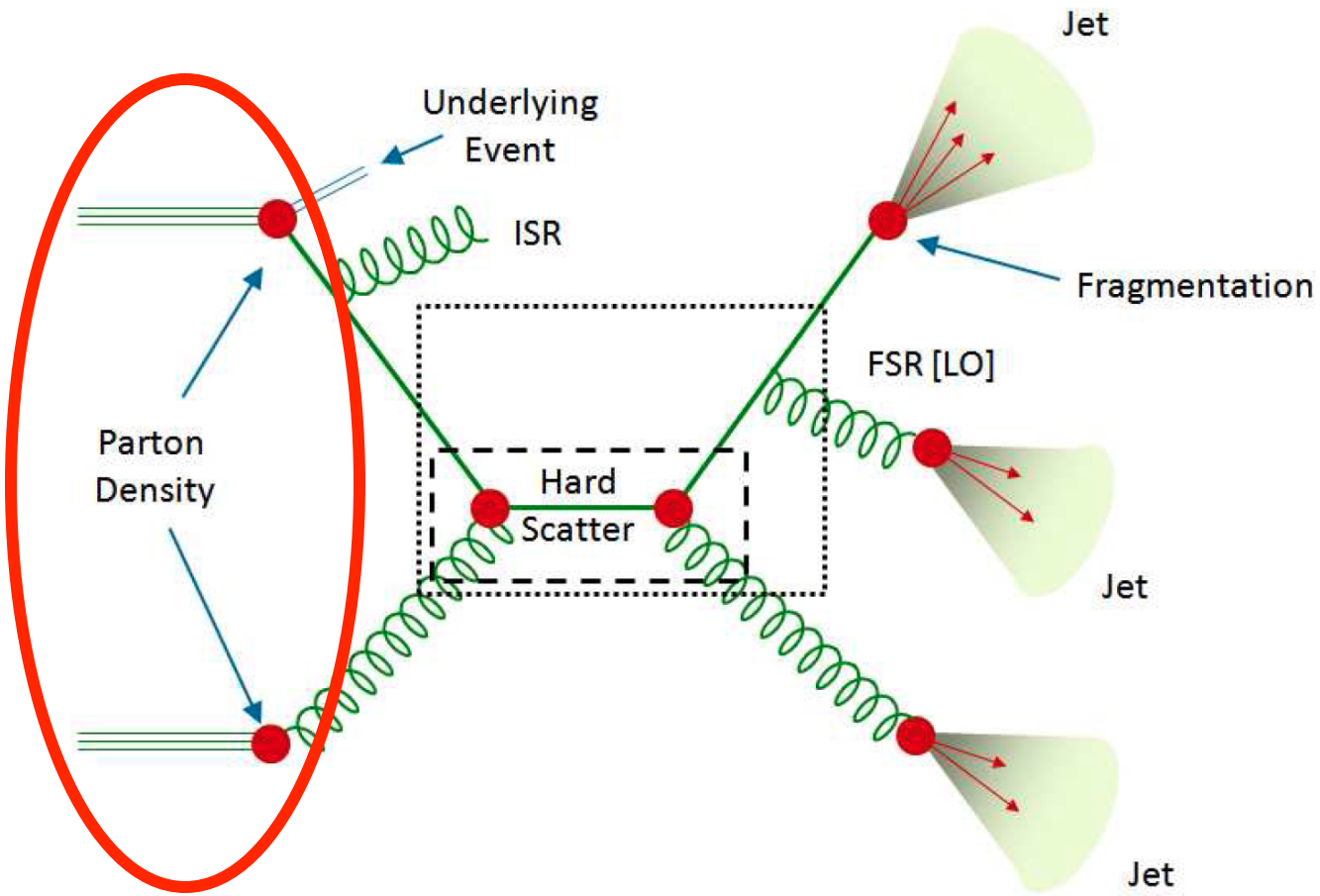
- Introduction
- Inclusive Jet production
  - at 7 TeV, at 8 TeV
  - AK5/AK7 ratio
- Dijet Production
  - Differential cross section at 7 TeV, at 8 TeV
  - Dijet mass and jet substructure
- Multi-jet Production
  - Colour coherence
  - 3-Jet Mass cross section
  - 3-jet to 2-jet cross section Ratio
  - Measurement of α_S

All data from published results are posted on the Durham database:
http://hepdata.cedar.ac.uk/

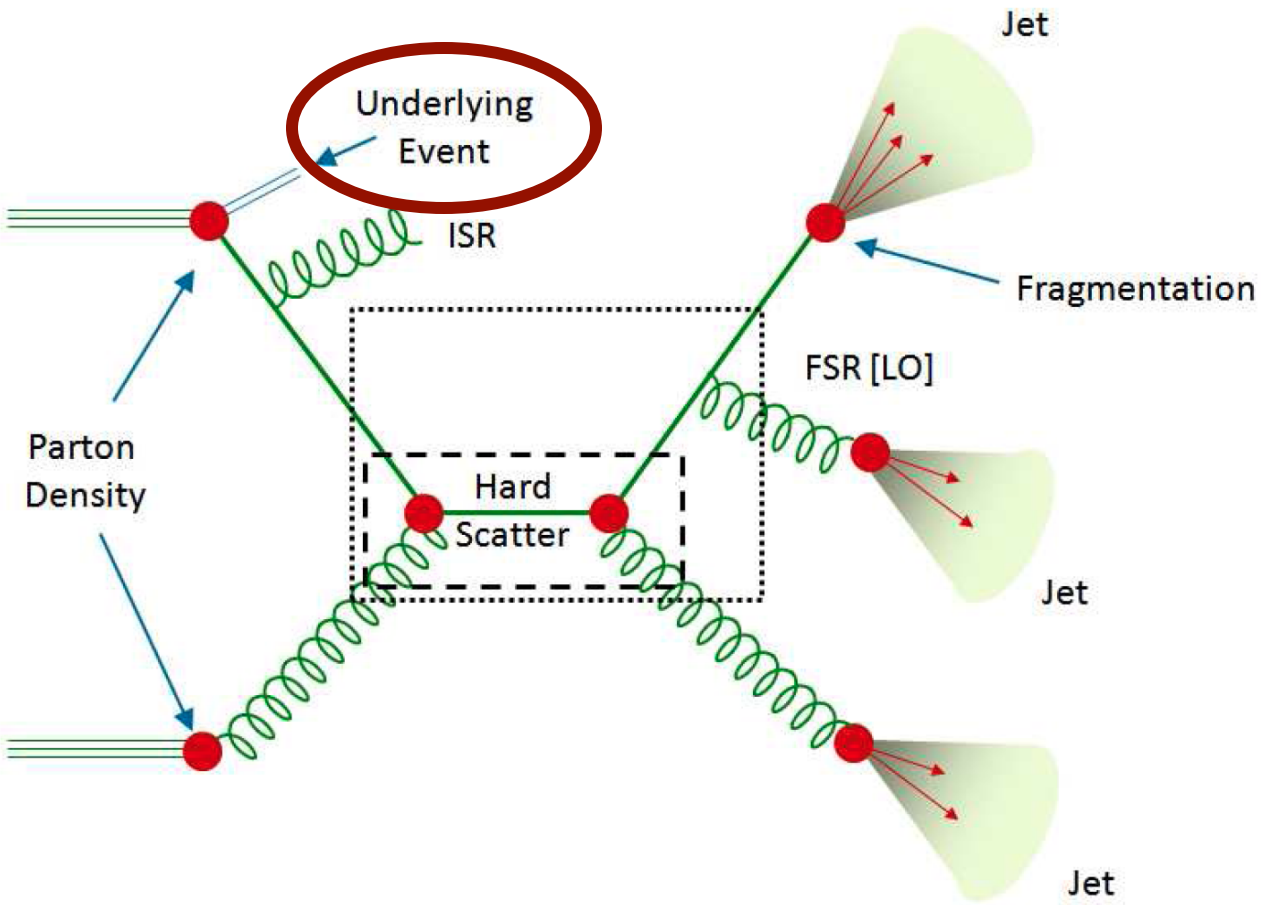
For all public results in CMS Standard Model Physics:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

QCD at Hadron Colliders

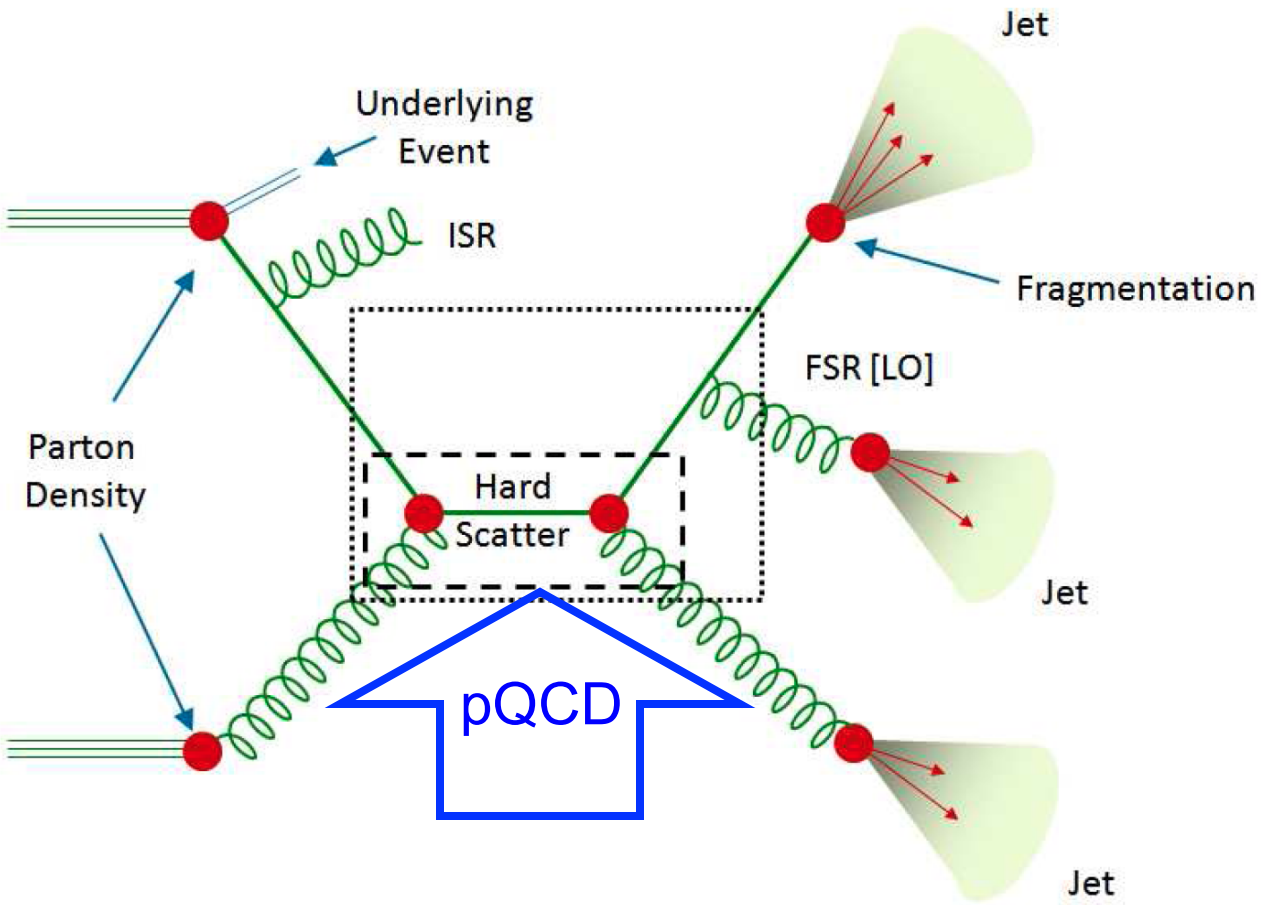
PDF's



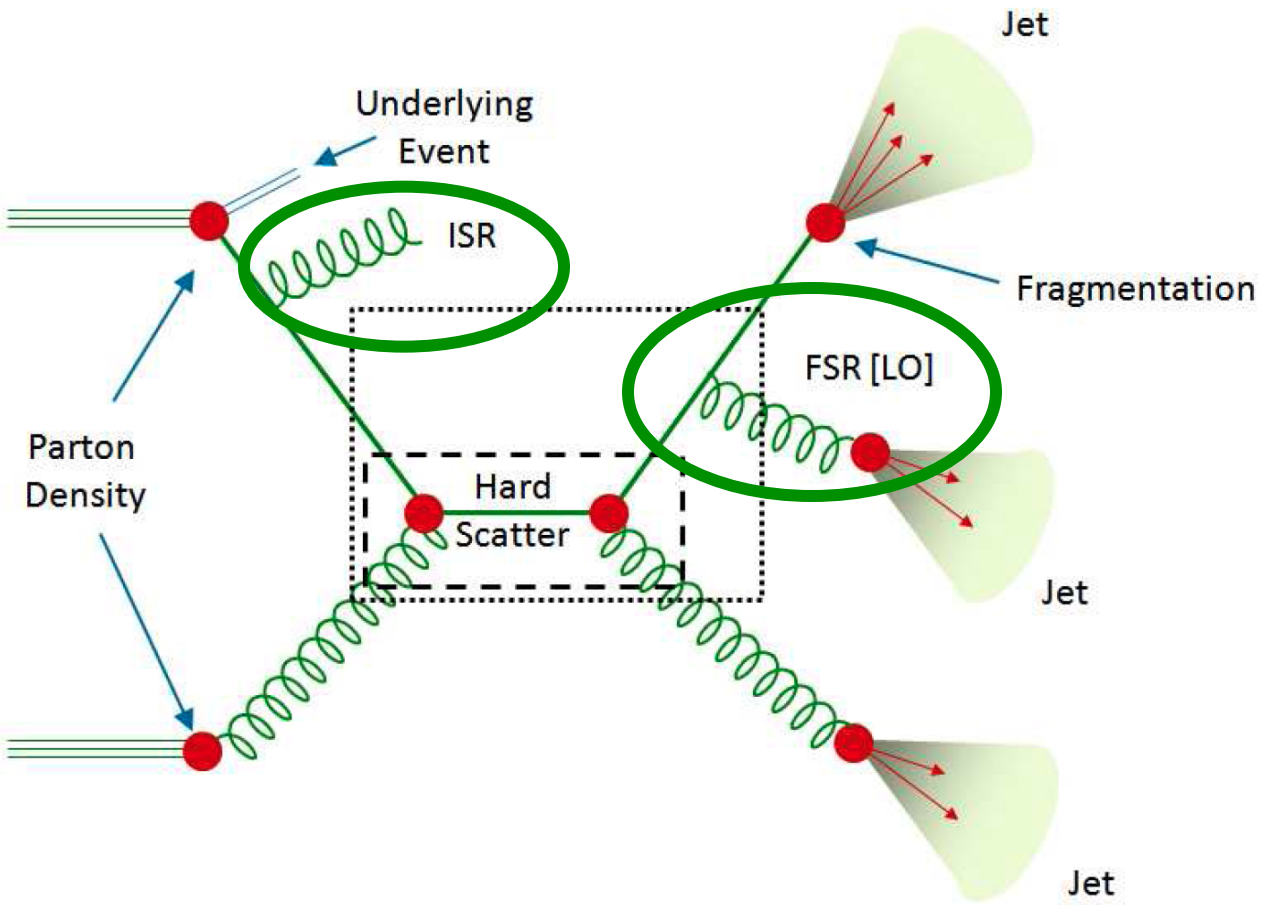
QCD at Hadron Colliders



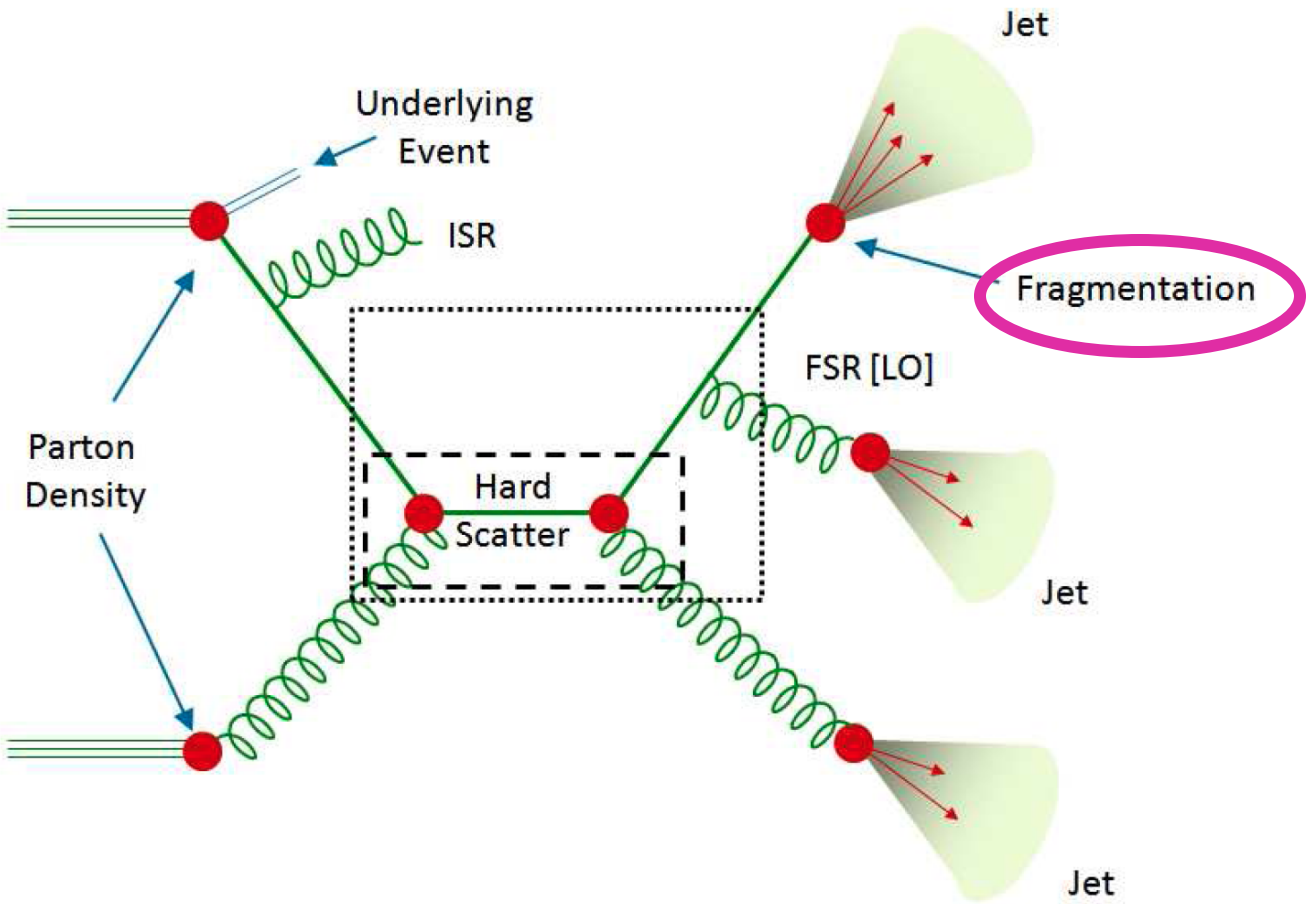
QCD at Hadron Colliders



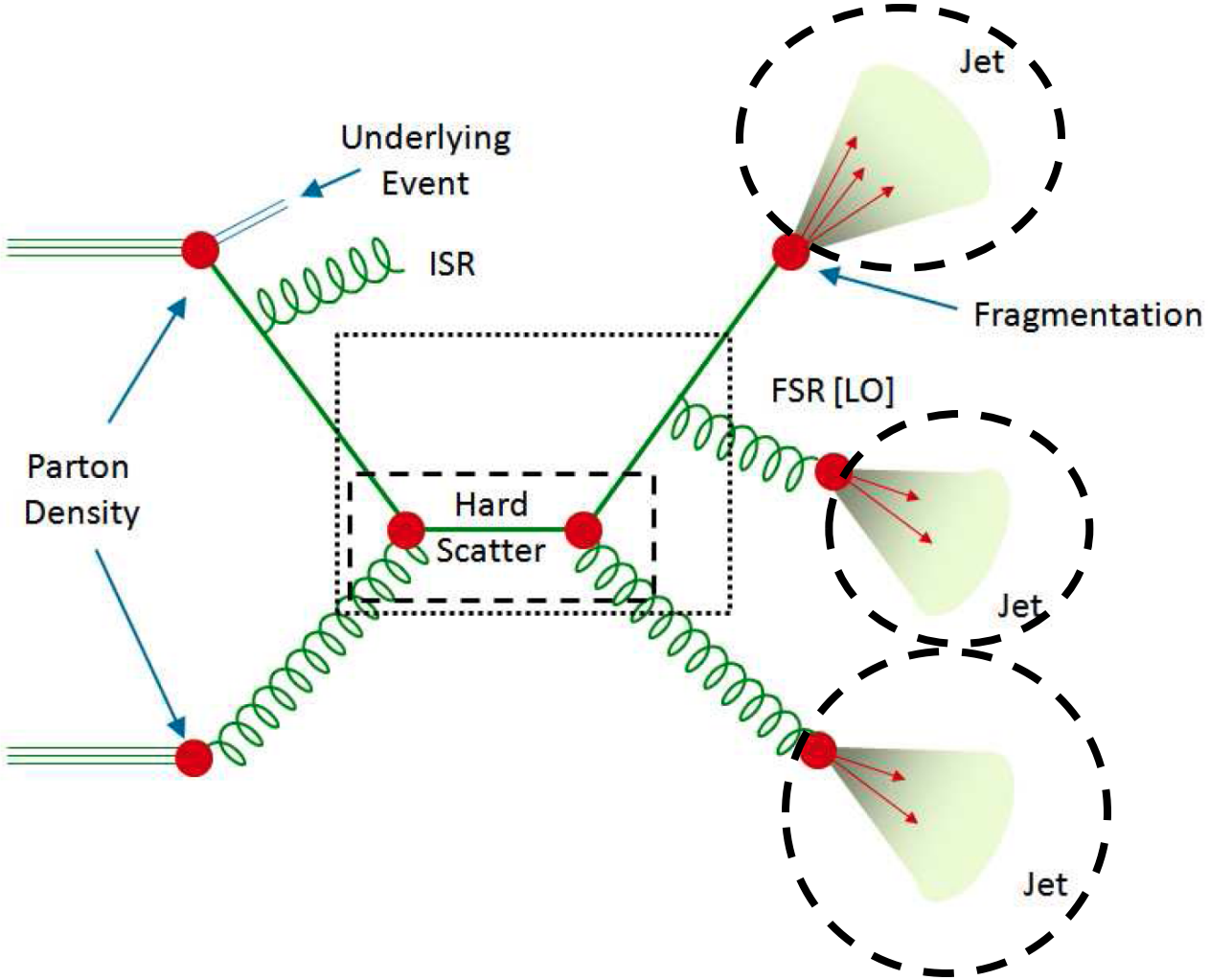
QCD at Hadron Colliders



QCD at Hadron Colliders

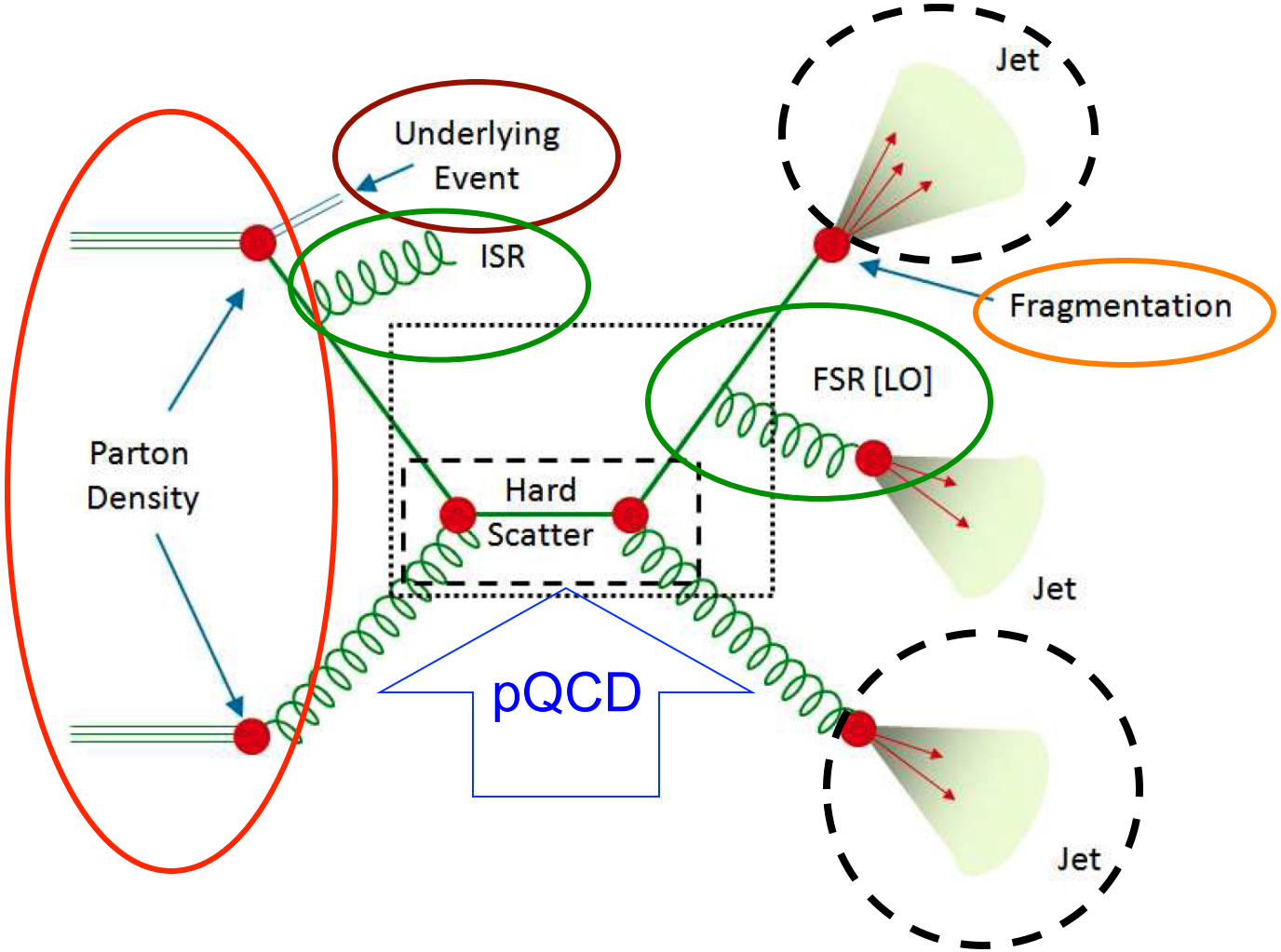


QCD at Hadron Colliders

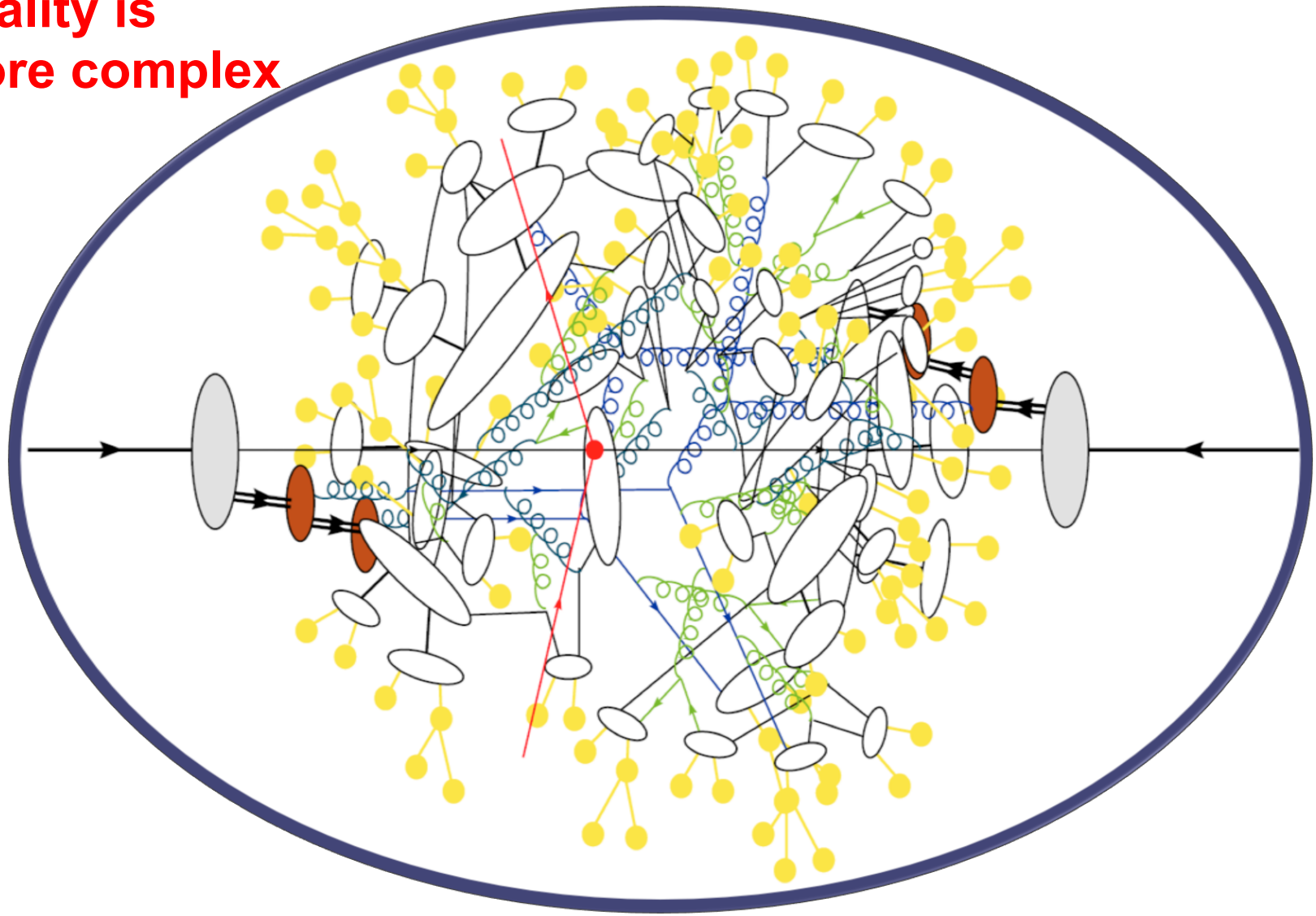


QCD at Hadron Colliders

PDF's

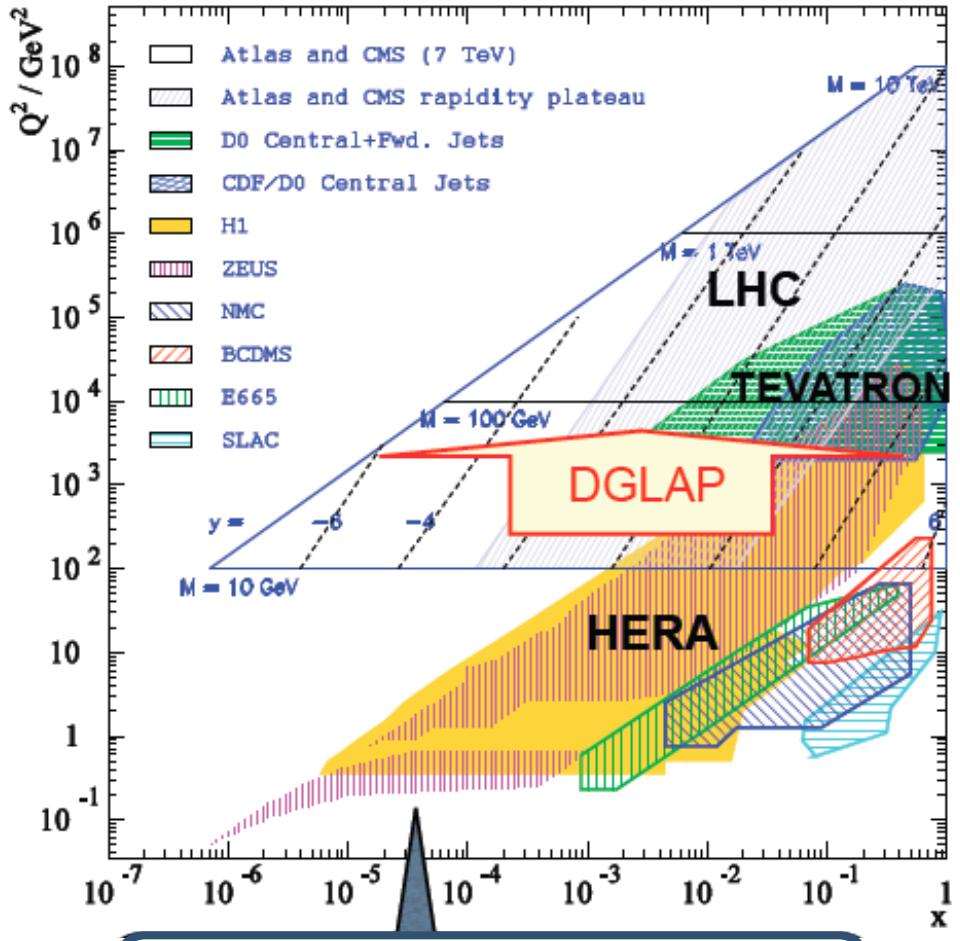


Reality is more complex



Why do we care about QCD?

- It is interesting
  - very rich theory: deserves exploration and understanding
- It is inevitable
  - hadron collisions: QCD is always present
- Important background for new physics searches
  - enormous cross section: QCD can hide many possible signals of new physics
- Introduces uncertainties on other measurements
  - e.g. uncertainties on the PDFs affect the Higgs properties
- With LHC data
  - probing new territory



experimental access to an enormous phase space ➔ stringent test of QCD

CMS: the detector

Total weight 14000 t
Diameter 15 m
Length 28.7 m

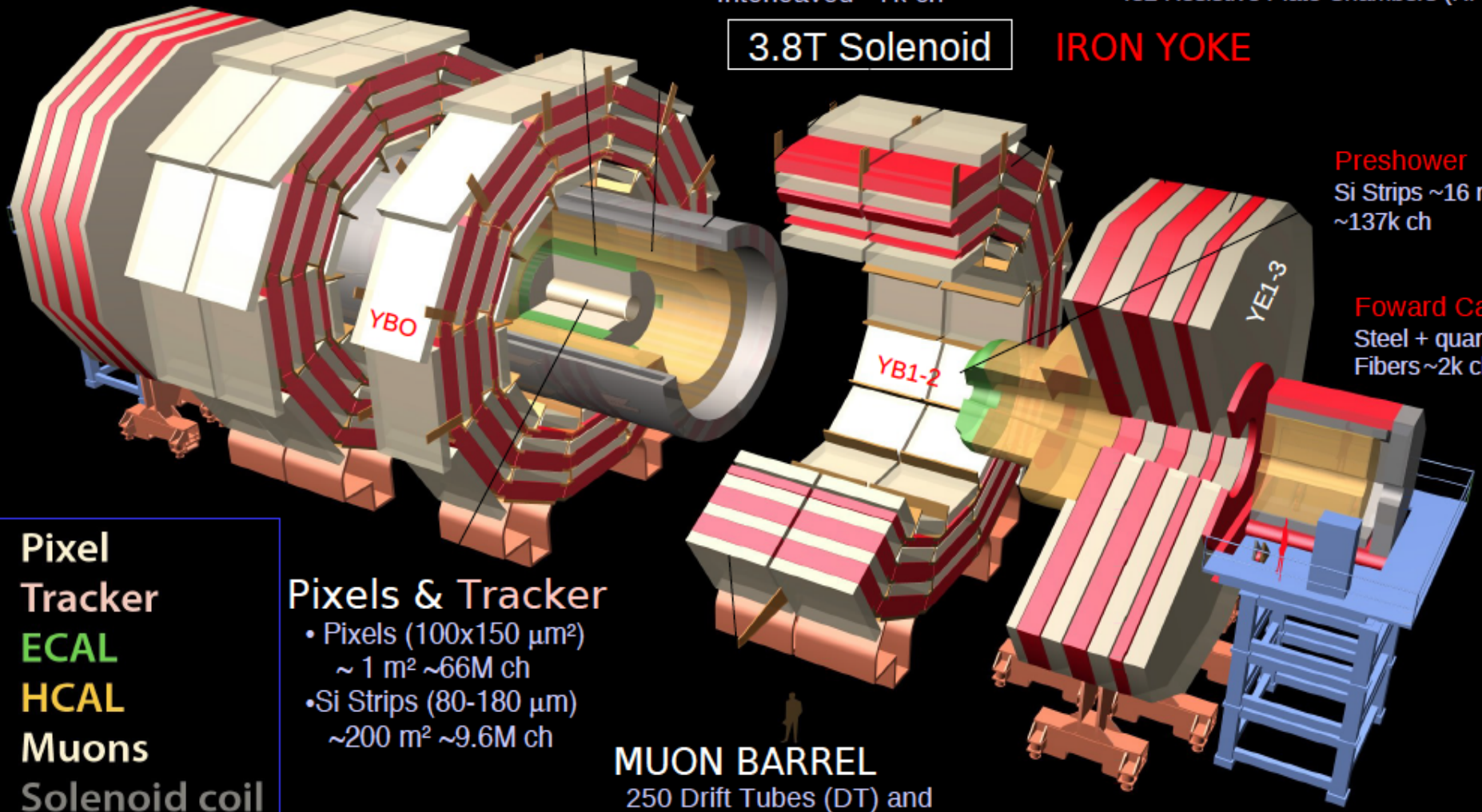
ECAL 76k scintillating $PbWO_4$ crystals

HCAL Scintillator/brass Interleaved ~7k ch

MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)

3.8T Solenoid

IRON YOKE



Preshower
Si Strips ~16 m²
~137k ch

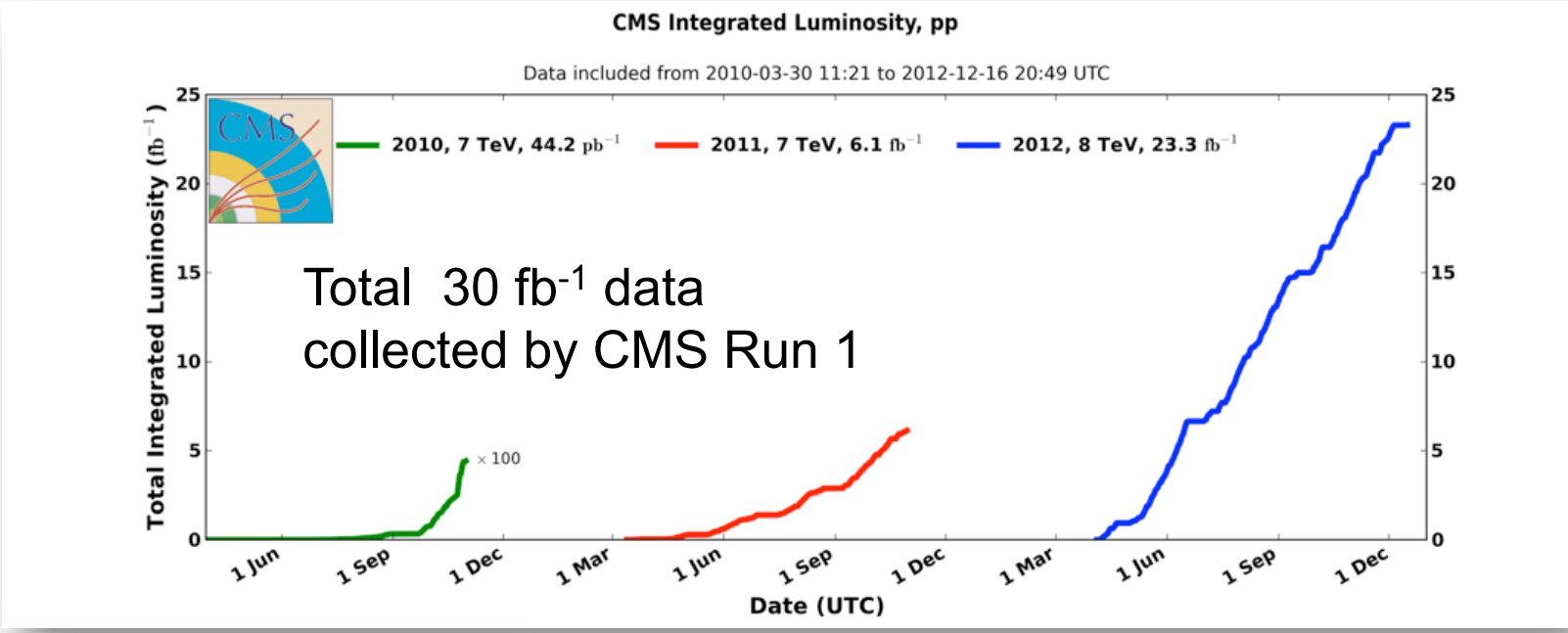
Foward Cal
Steel + quartz Fibers ~2k ch

Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

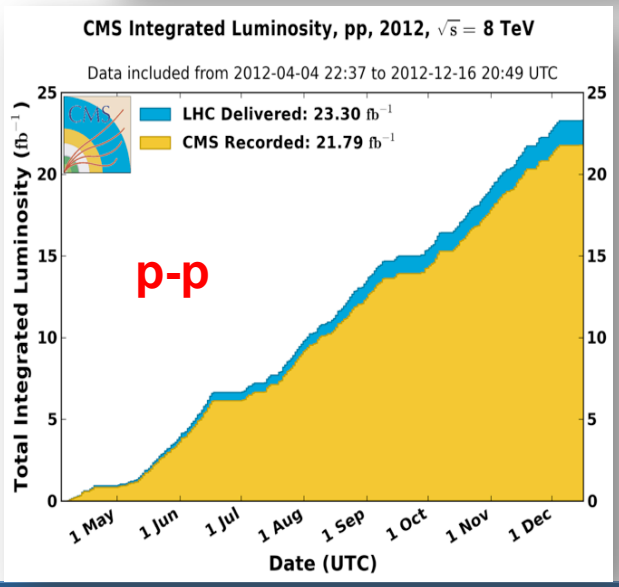
Pixels & Tracker
- Pixels (100x150 µm²) ~ 1 m² ~66M ch
- Si Strips (80-180 µm) ~200 m² ~9.6M ch

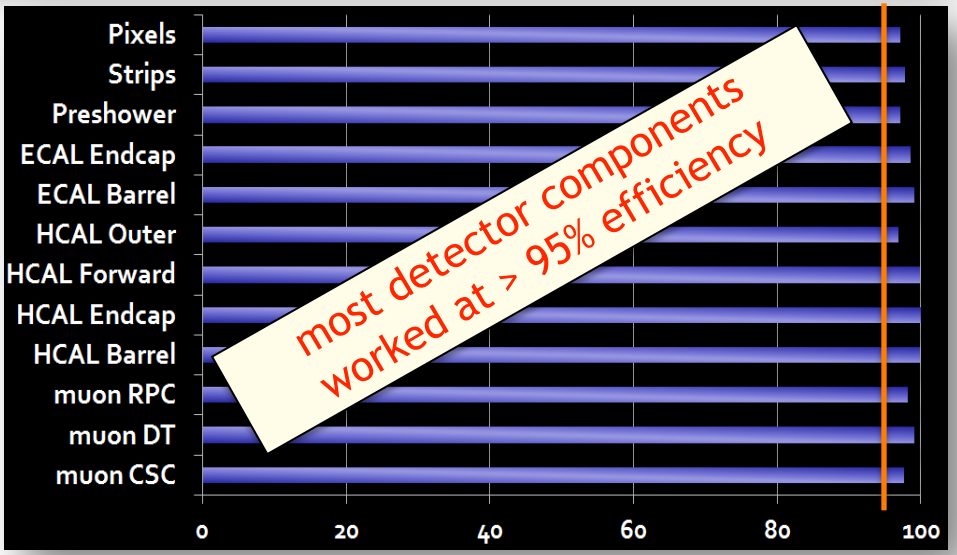
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

Thanks LHC for Fantastic 3 years!



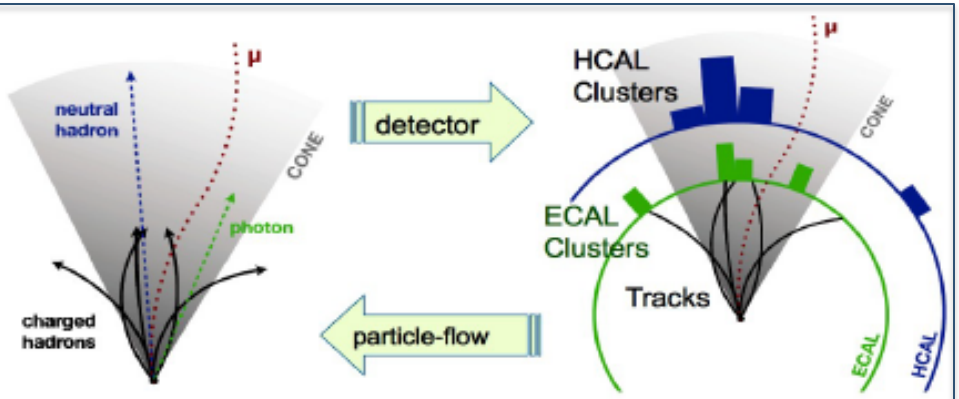
Total 30 fb^{-1} data collected by CMS Run 1



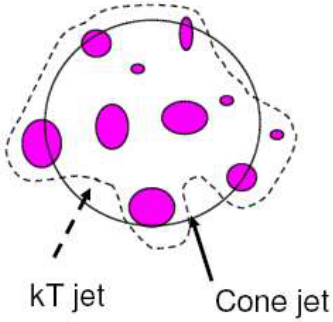


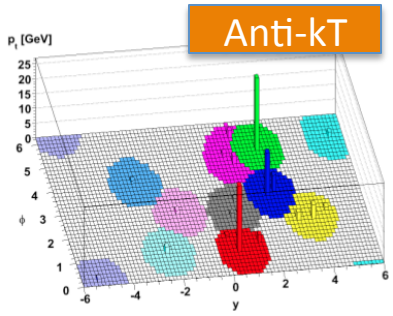
Jet Reconstruction

Particle-Flow (PF) algorithms use:
e, μ, γ, charged & neutral hadrons
as building blocks for
jets, b-jets, τ's, ν (miss E_T)



- Fixed cone algorithms:
  - Iterative Cone (CMS) / JetClu (ATLAS)
  - Seedless Infrared Safe Cone (SISCone)





- Successive recombination algorithms:

$$d_{ij} = p_{T,i}^{2p} \qquad d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{D^2}$$

p=1 -> k_T jet algorithm
p=0 -> CA jet algorithm
p=-1 -> "Anti-k_T" jet algorithm

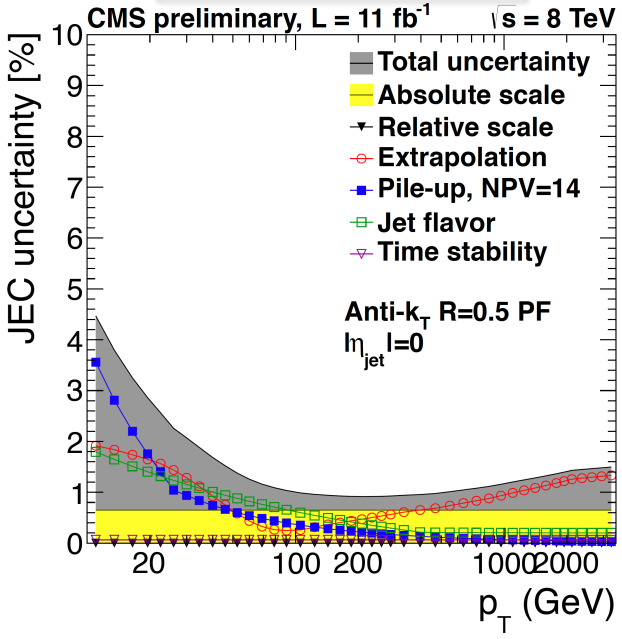
- Soft particles will first cluster with hard particles before among themselves
- Almost a cone jet near hard partons
- No merge/split

Jet Energy Calibration

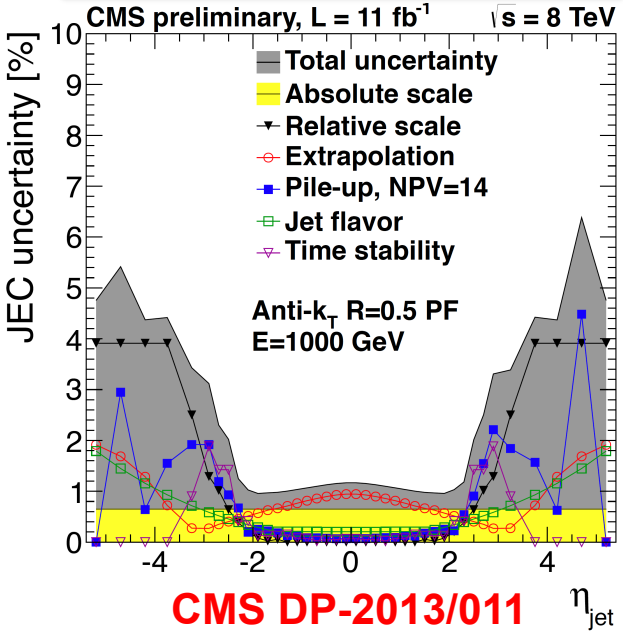
- Jet Energy Correction is necessary to measure the correct energy spectrum of Jets
- The main three type of corrections required are OffSet (pile up subtraction), Relative(for η dependent response) and Absolute(for p_T dependent response) + Residual corrections. [JINST 6 (2011) P11002]
  - Offset −> Subtracting
  - Relative −> Dijet balance
  - Absolute −> γ + jet and Z + jet (p_T balance, MPF)

JEC (Jet Energy Correction) uncertainty ~1% for central high-pT jets

JEC unc vs p_T

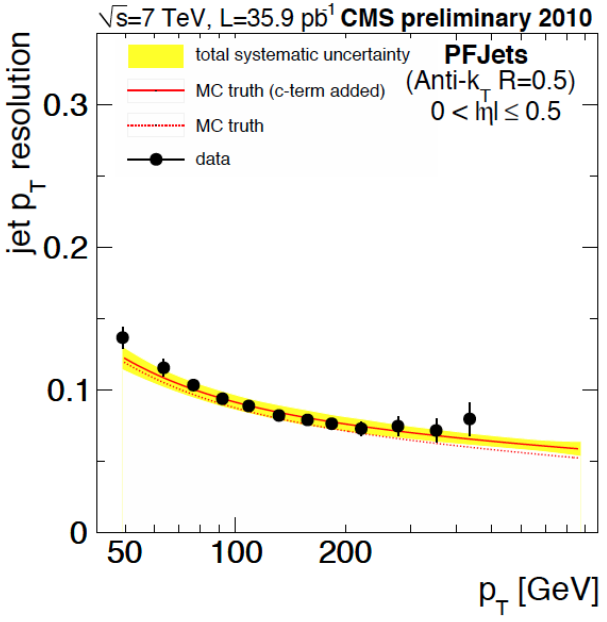


JEC unc vs η @ E=1 TeV



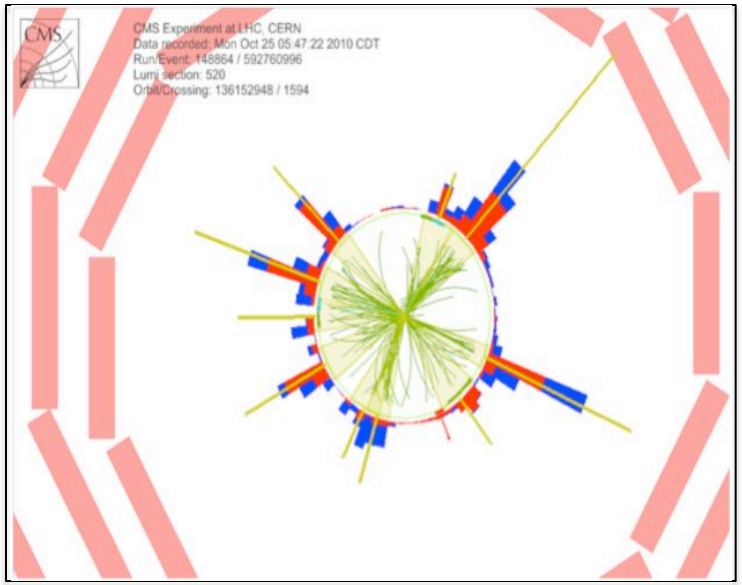
CMS DP-2013/011

Jet p_T Resolution



Inclusive Jet Production

- Inclusive Jet Cross Section @ 7 TeV [QCD-11-004]
  Phys. Rev. D **87** (2013) 112002
- Inclusive Jet Cross Section @ 8 TeV [SMP-12-012, FSQ-12-031]
- Inclusive jet AK5/AK7 cross section ratio @ 7 TeV [SMP-13-002]



The Legacy Measurement

UA2: PLB 118 (1982)
CERN pp-bar $\sqrt{s}$ = 540 GeV

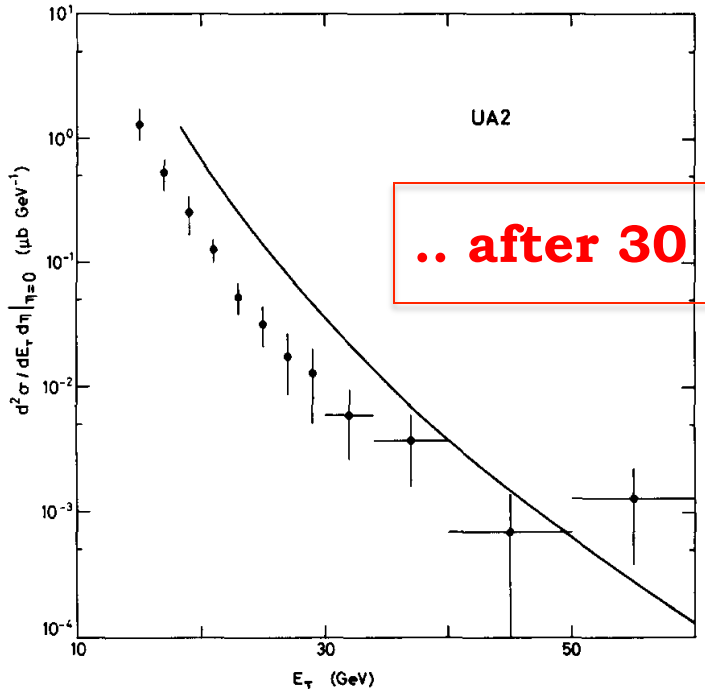
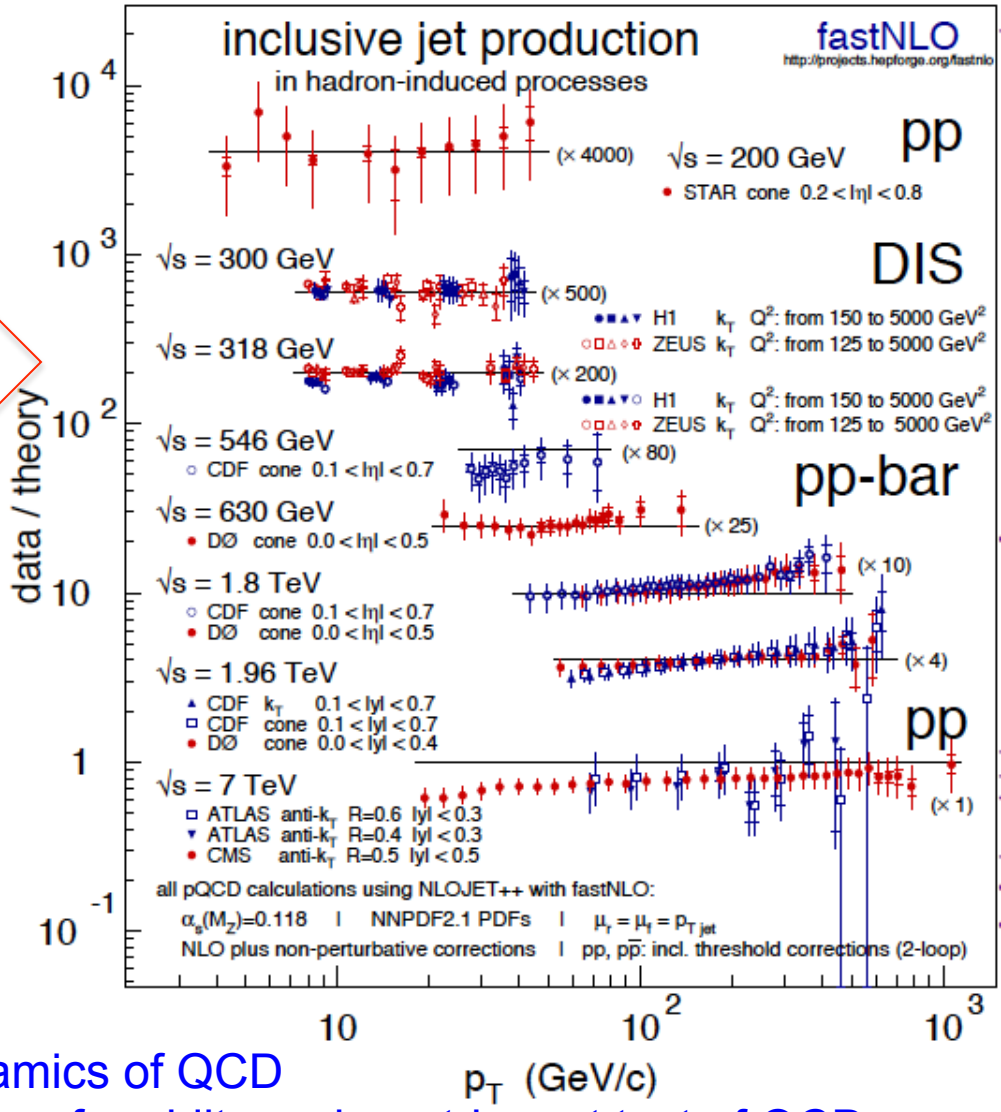


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

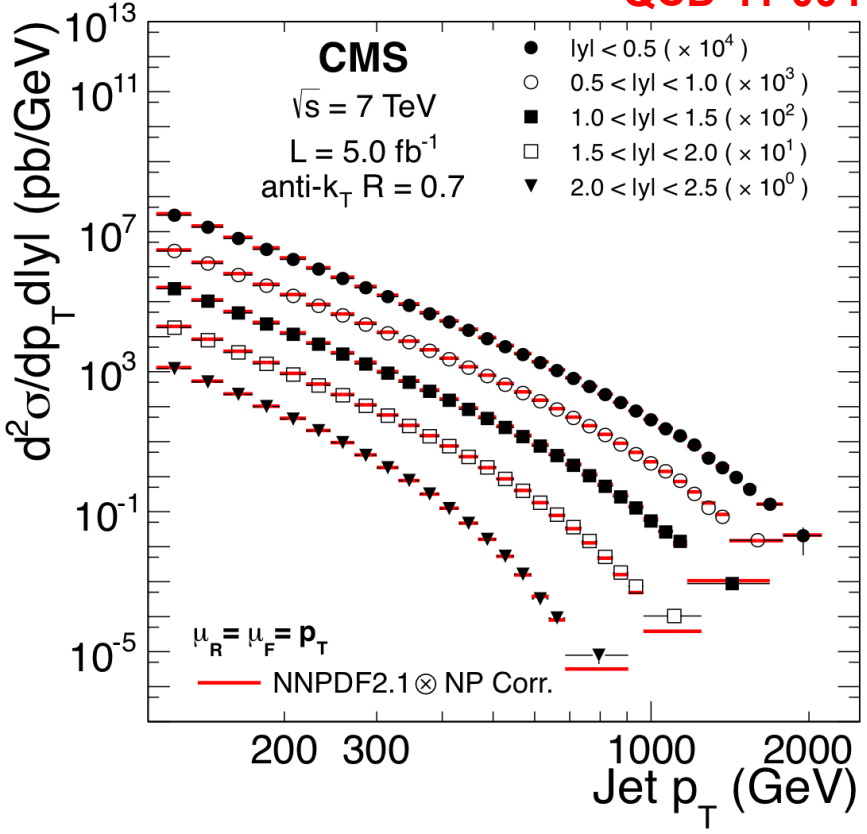
.. after 30 years

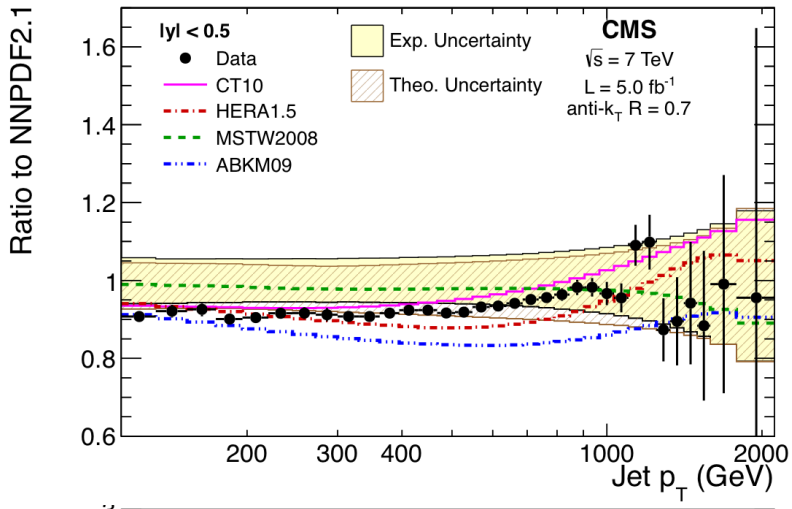


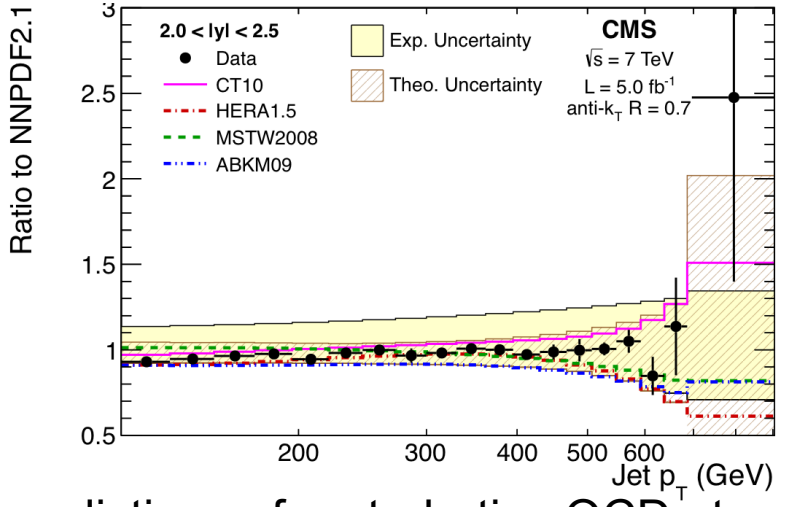
- Inclusive jet production probes the dynamics of QCD
  - counting the number of jets as a function of rapidity and p_T stringent test of QCD
  - PDFs, strong coupling constant, perturbative calculations

Inclusive Jet Differential Cross section @ 7 TeV

QCD-11-004



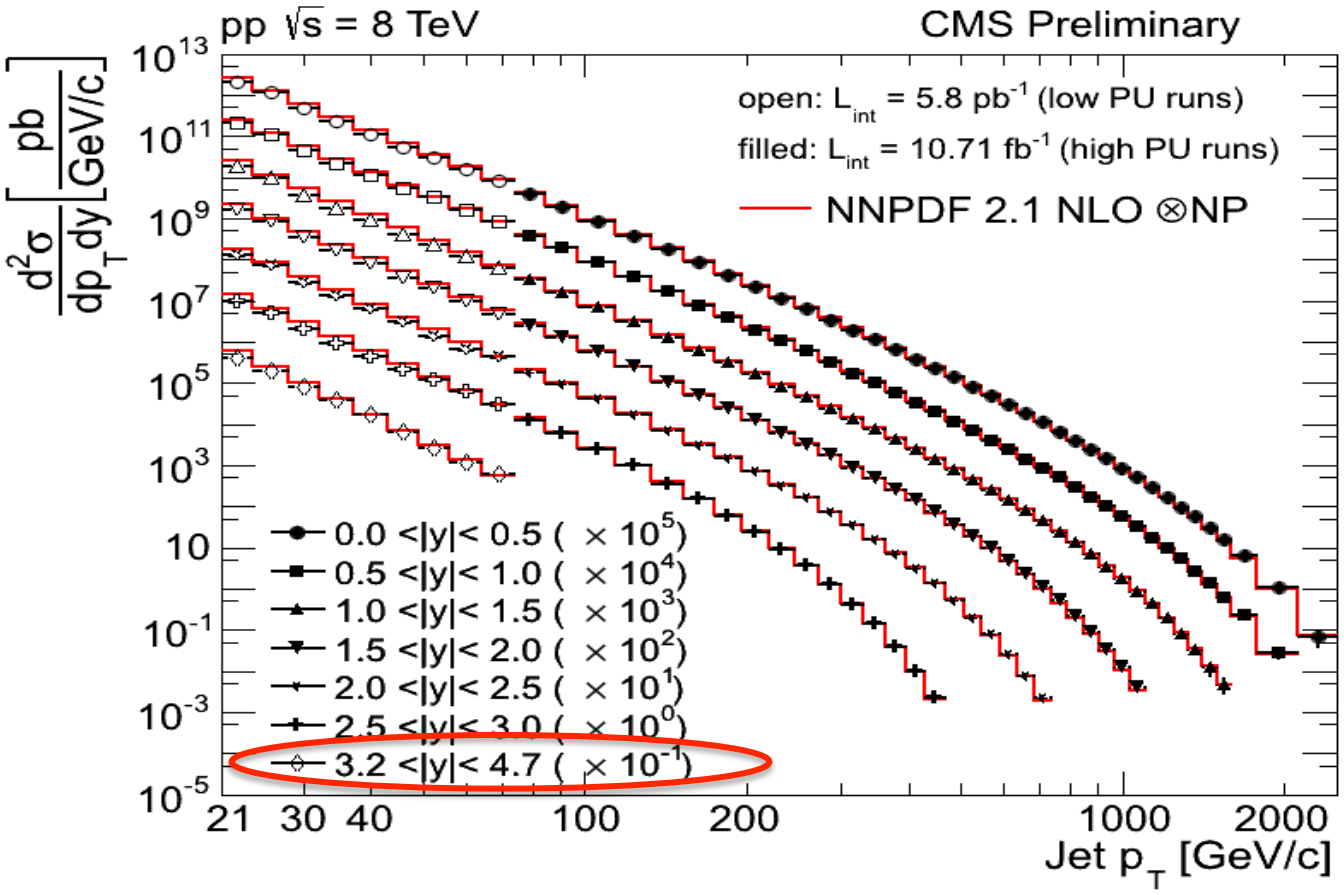




- Double differential Inclusive jet cross-section measured from p_T 0.1 to 2 TeV
- Measured cross sections agree with the predictions of perturbative QCD at next-to-leading order obtained with five different PDF sets
- Theoretical and experimental uncertainties are comparable, even at the limits of the experimental phase space

Inclusive Jet Differential Cross section @ 8 TeV

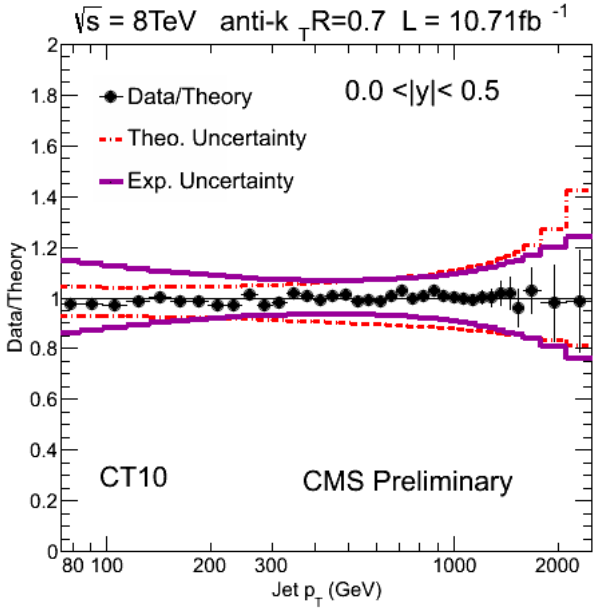
SMP-12-012
FSQ-12-031

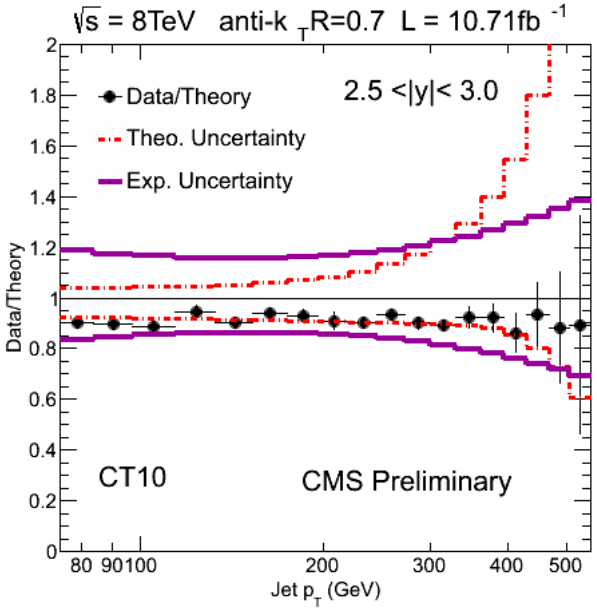


- Measurement at 8 TeV up to **|y| = 4.7**
- **O(14)** magnitude in cross section
- Comparisons to pQCD NLO⊗NP
  [NP: corrections for non-perturbative effects (MPI and hadronization):
  20% (~100 GeV) ➔ 1% (~2.5 TeV)]

Theory Comparisons

SMP-12-012





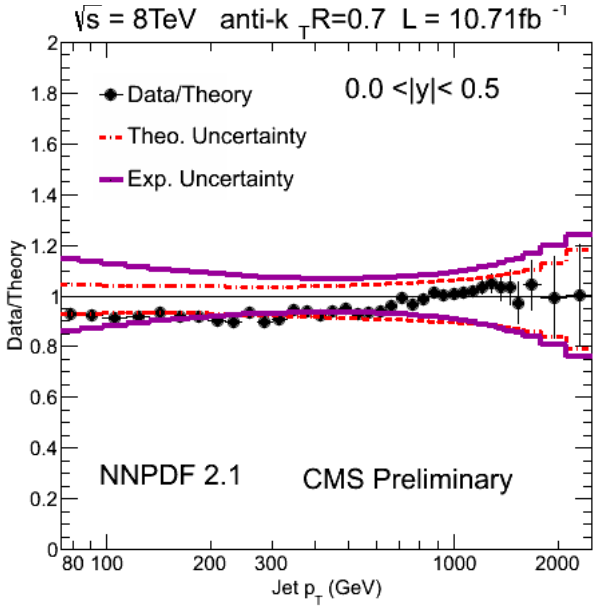
Experimental uncertainty:

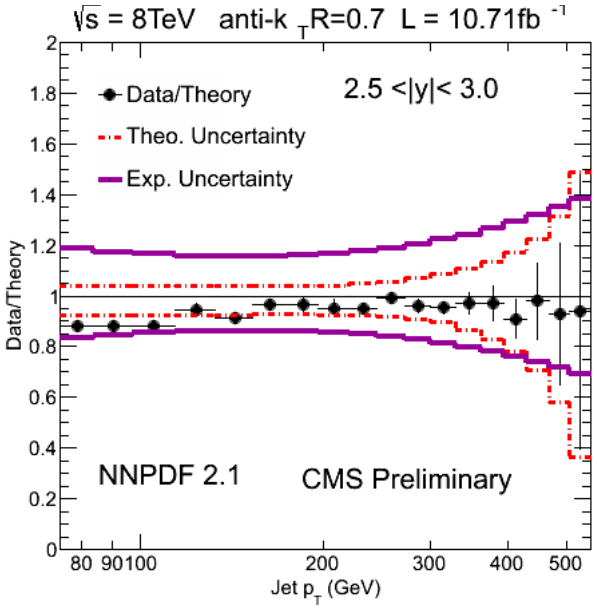
- JES(12%-30%),
- Luminosity(4.4%)
- Unfolding(1%-10%)
- Total: 15%-40%

Theory uncertainty:

- PDF(5%-30%)
- Scale(5%-40%)

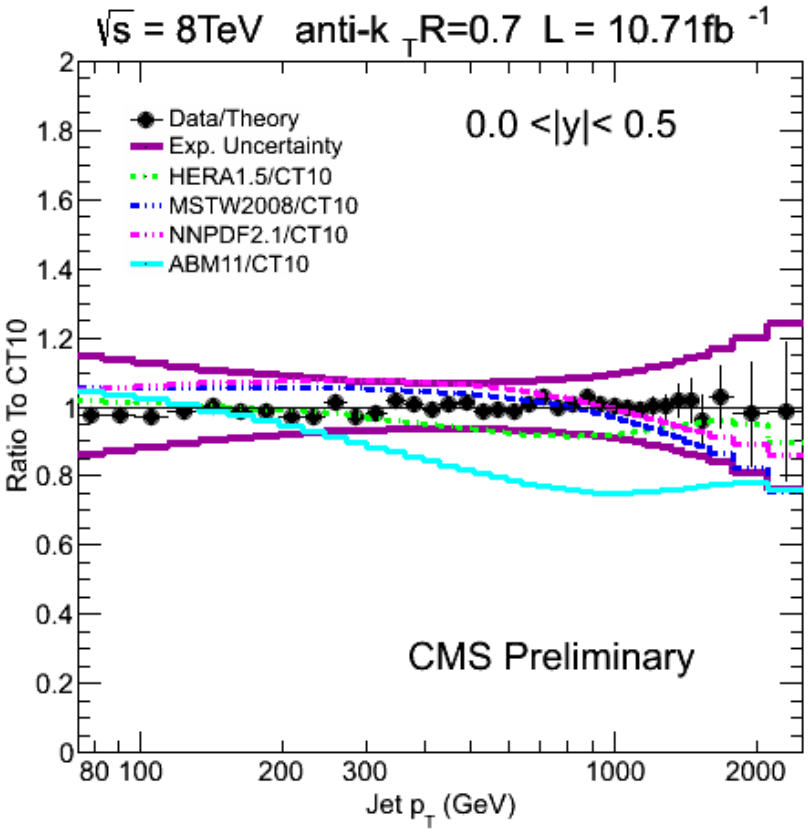
PDF uncertainty for CT10 in outer bins 100%

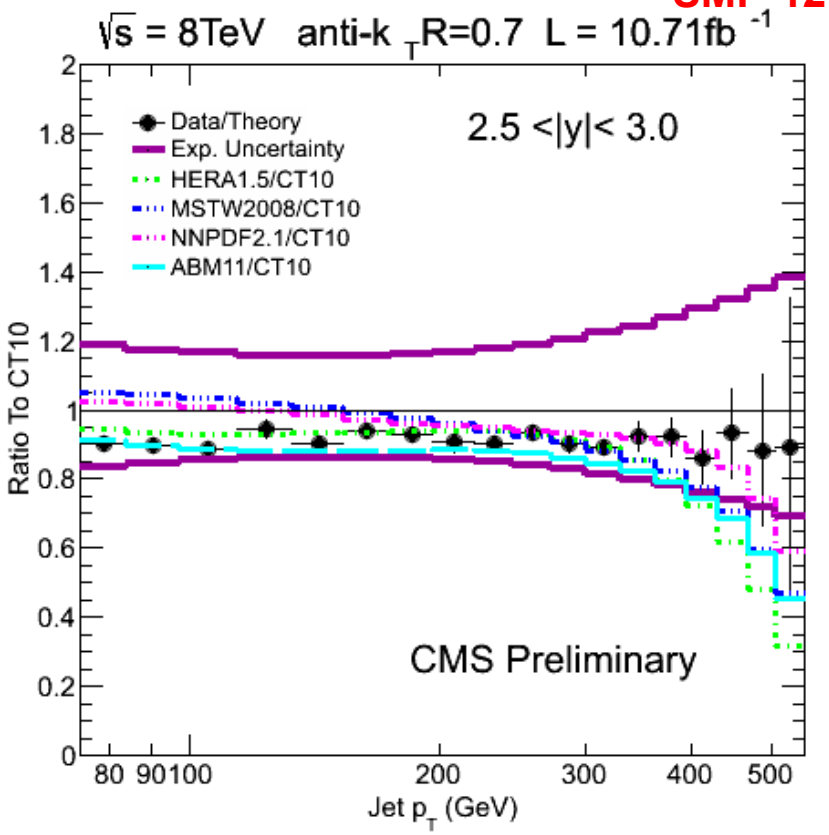




Comparison among Different PDFs

SMP-12-012

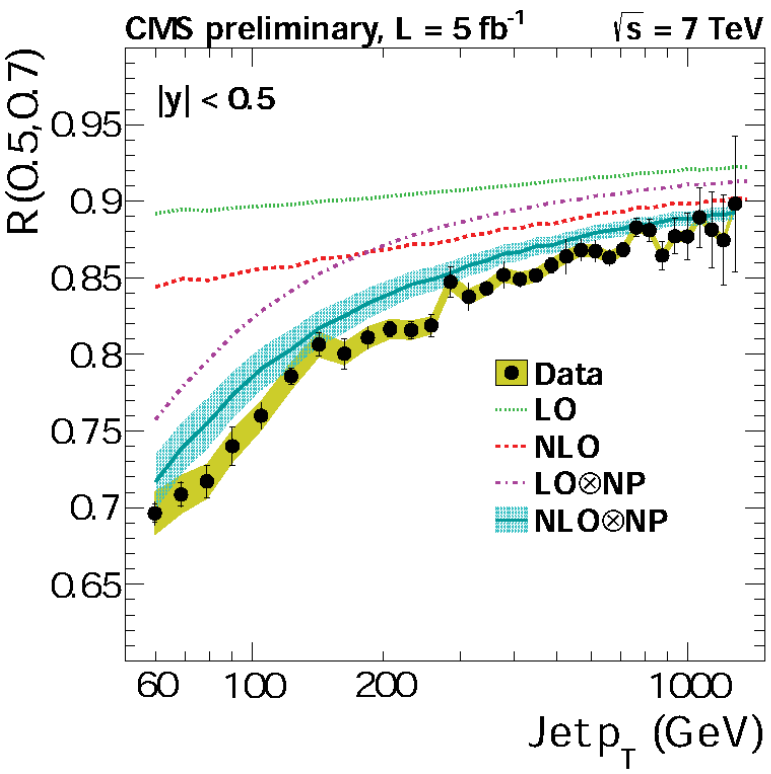


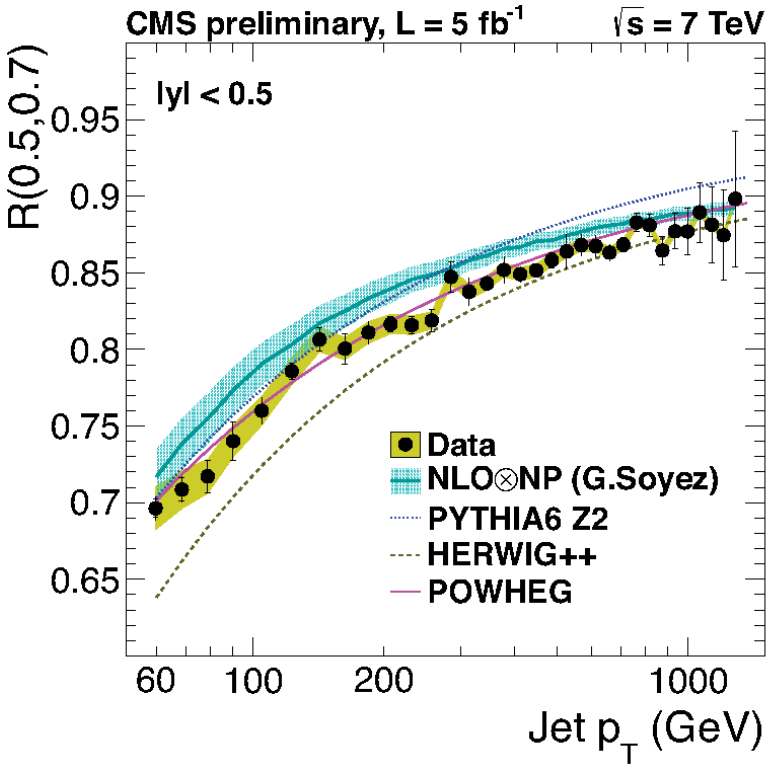


- Data over theory compared to ratio with other PDF sets for CT10
- The theory predictions are computed for five different PDF sets, viz. ABM11, HERA1.5, CT10, MSTW2008, NNPDF2.1
- In the central rapidity region (0.0<|y|<0.5) different theory predictions are in agreement with data except ABM11
- The fluctuations are covered by total theoretical and experimental uncertainty bands

Inclusive Jet AK5/AK7 Cross Section Ratio

- Motivation: AK5/Ak5 ratio gives insight to QCD effect beyond fixed order
- Measurement at √s=7 TeV with different jet sizes R=0.5 (AK5), 0.7 (AK7)
- Ratio of cross sections R(0.5, 0.7) vs p_T and rapidity



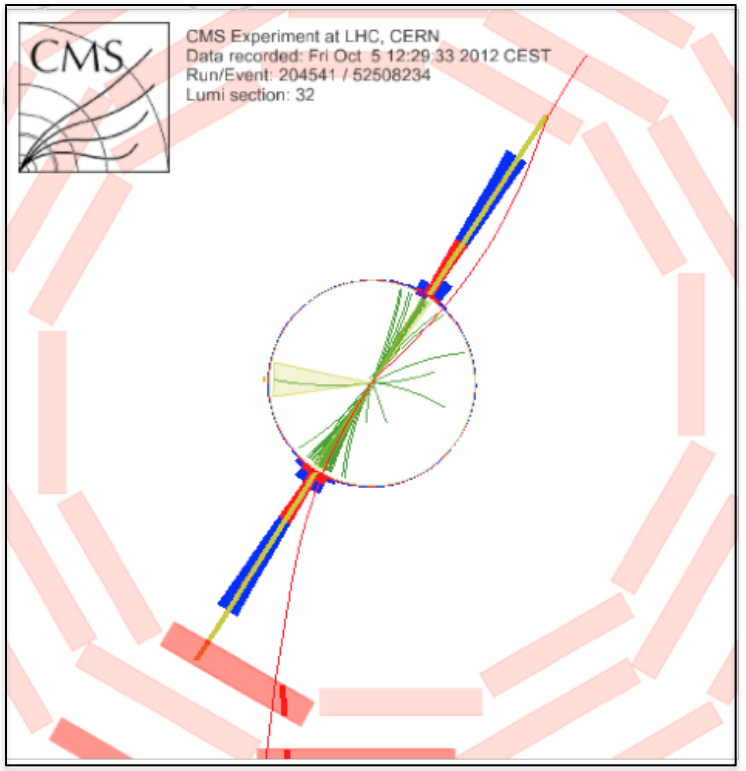


SMP-13-002

- Several systematic uncertainties cancel in ratio
- The ratio gradually increases towards unity with increasing Jet-p_T.
- Powheg(NLO+PS) prediction has the describes the data best

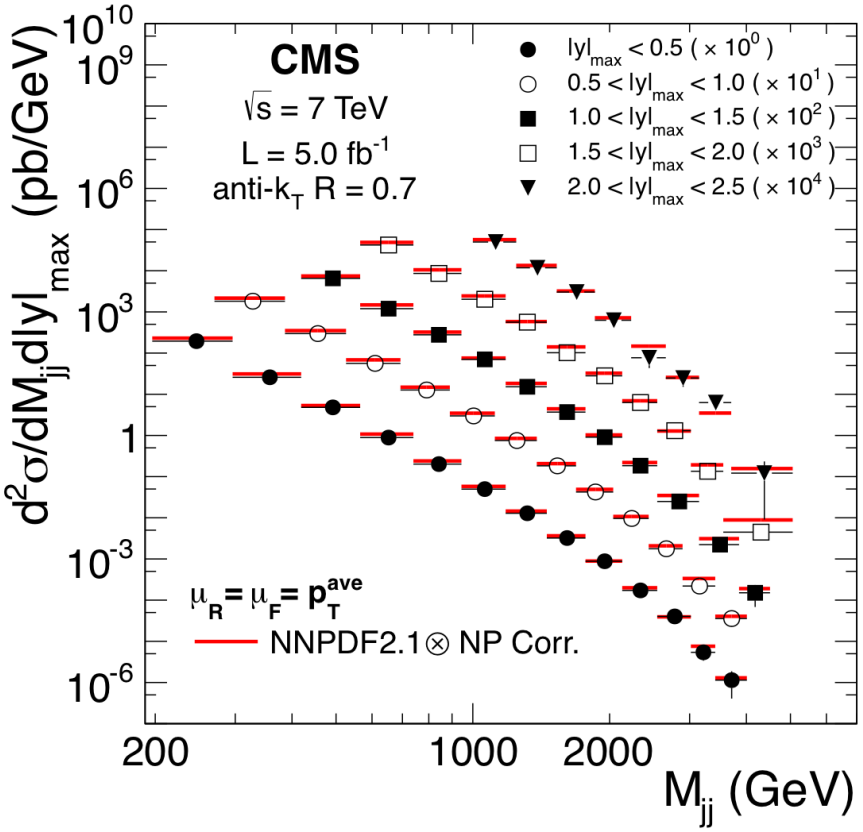
Dijet Production

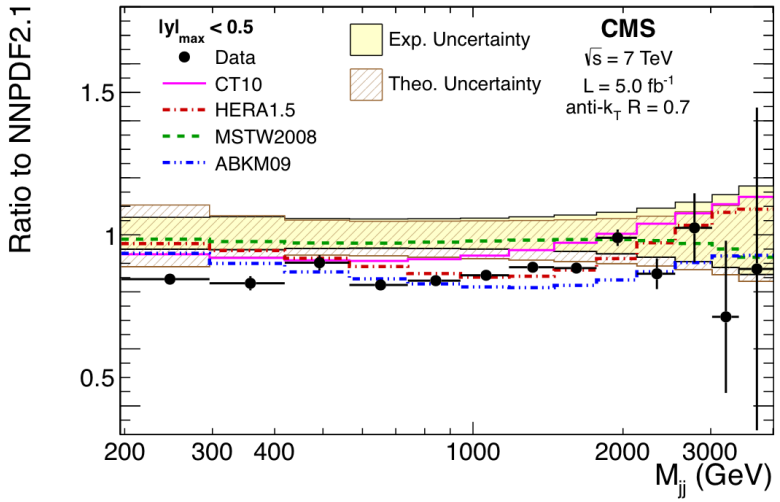
- Dijet Differential Cross Section @ 7 TeV [QCD-11-004]
  Phys. Rev. D **87** (2013) 112002
- Dijets and V+jets, jet mass and substructure at 7 TeV [SMP-12-019]
  JHEP **05** (2013) 090

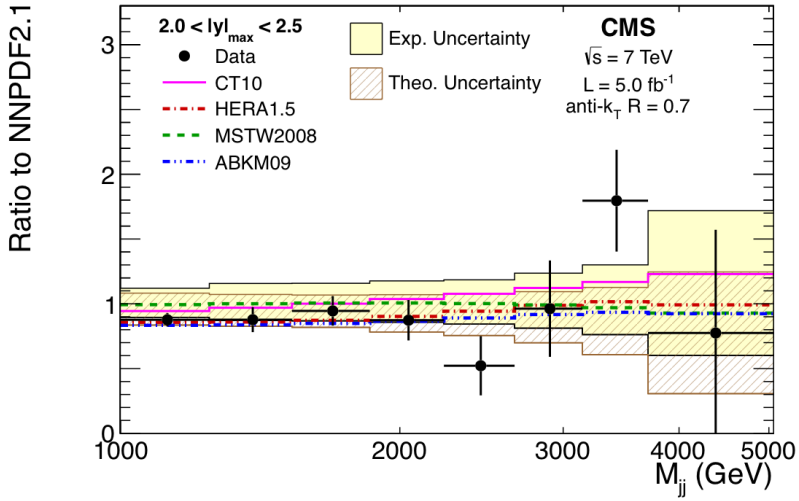


Dijet Cross Section @ 7 TeV

QCD-11-004



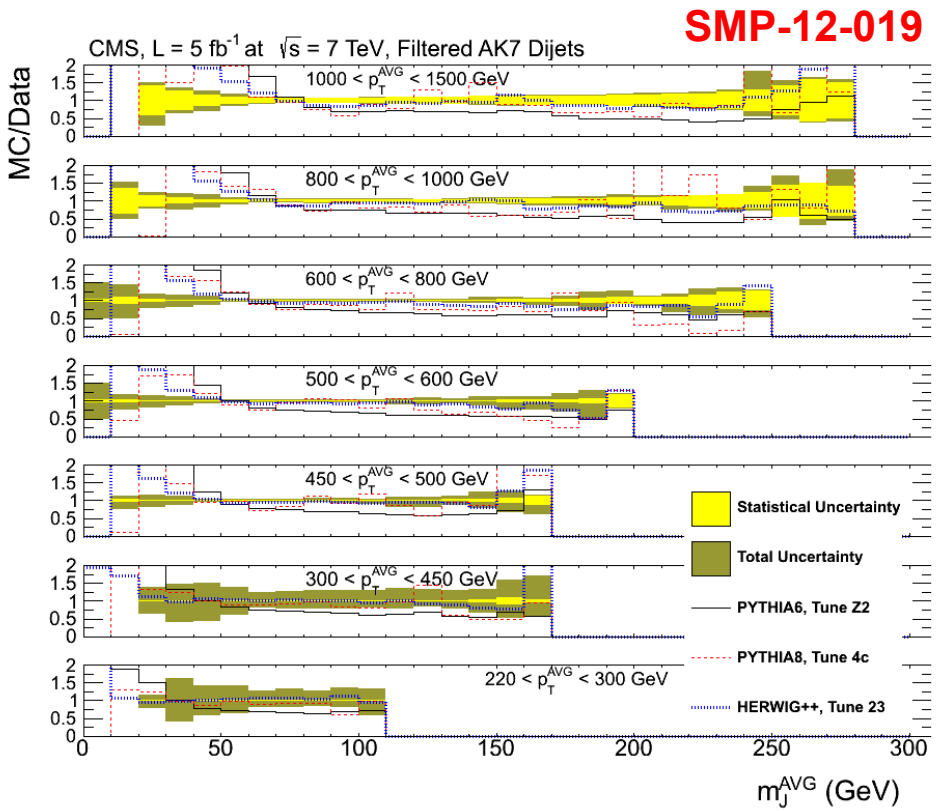


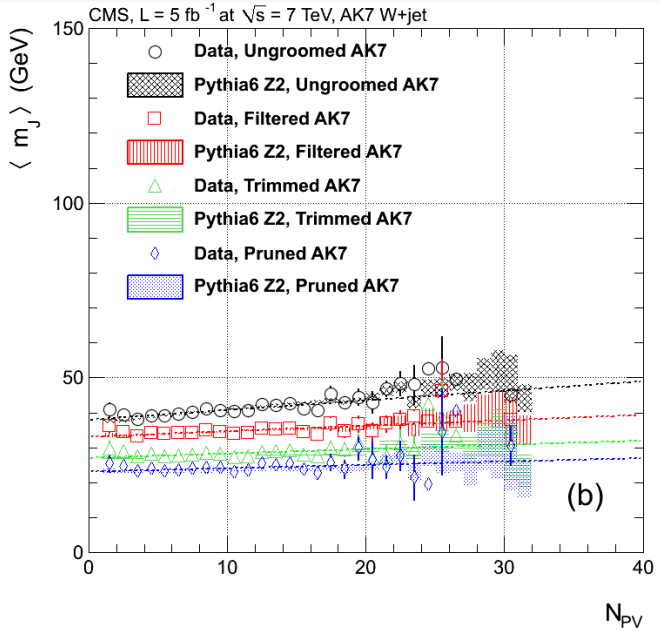


- Reach up to M_{jj} ~ 5.5 TeV
- Complementary to Inclusive jets
- Agreement with pQCD@NLO⊗NP

Dijet Mass and Jet Substructure

- Differential distributions in jet mass for inclusive dijet events, defined through the anti-k_T algorithm for a size parameter of 0.7 for jets groomed through filtering, trimming, and pruning.





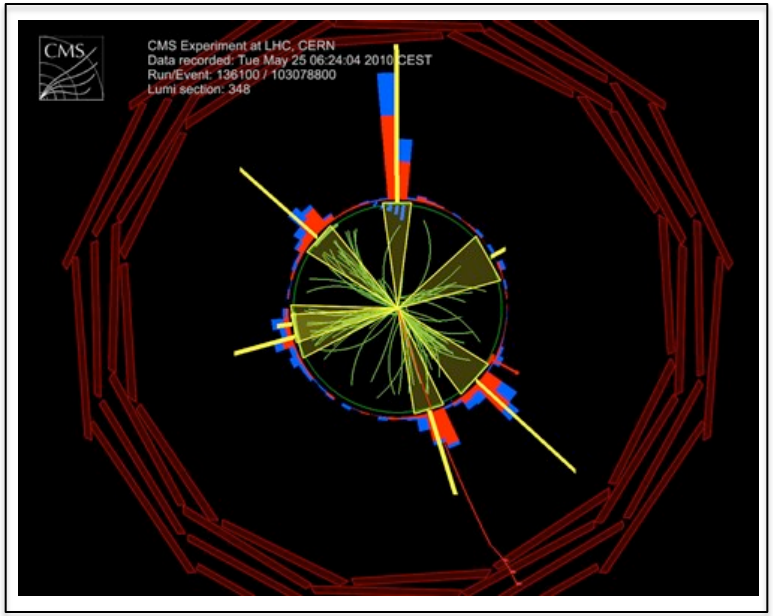
The intrinsic stability of these algorithms to pileup effects contribute to a more rapid and widespread use of these techniques in future high-luminosity runs at the LHC.

- Better agreement at larger jet masses.
- Trimming and pruning algorithms provide an important benchmark for their use in searches for massive particles.

➢ More details in Ivan Marchesini's talk on Jet substructure (Today at 3 pm)

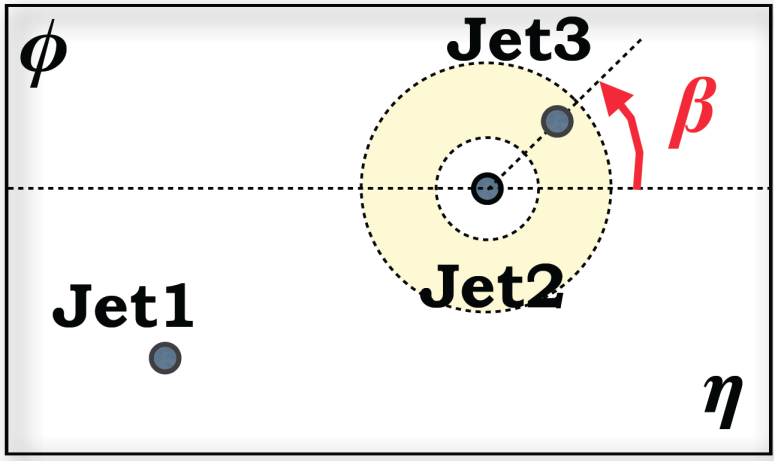
MultiJet Production

- Colour Coherence [SMP-12-010]
- 3-Jet Mass cross section [SMP-12-027]
- 3/2 Inclusive Jet Cross section Ratio [QCD-11-003] arXiv:1304.7498
- Measurement of α_S [SMP-12-027, QCD-11-003]



Colour Coherence Effect

- In QCD color coherence effects are due to the interference of soft gluon radiation emitted along color connected partons
- In LO model with FSR radiation the 3rd jet tends to be between second jet and proton remnant
- Measure the angular distribution of softer 3rd jet around the 2nd highest-p_T jet in the event



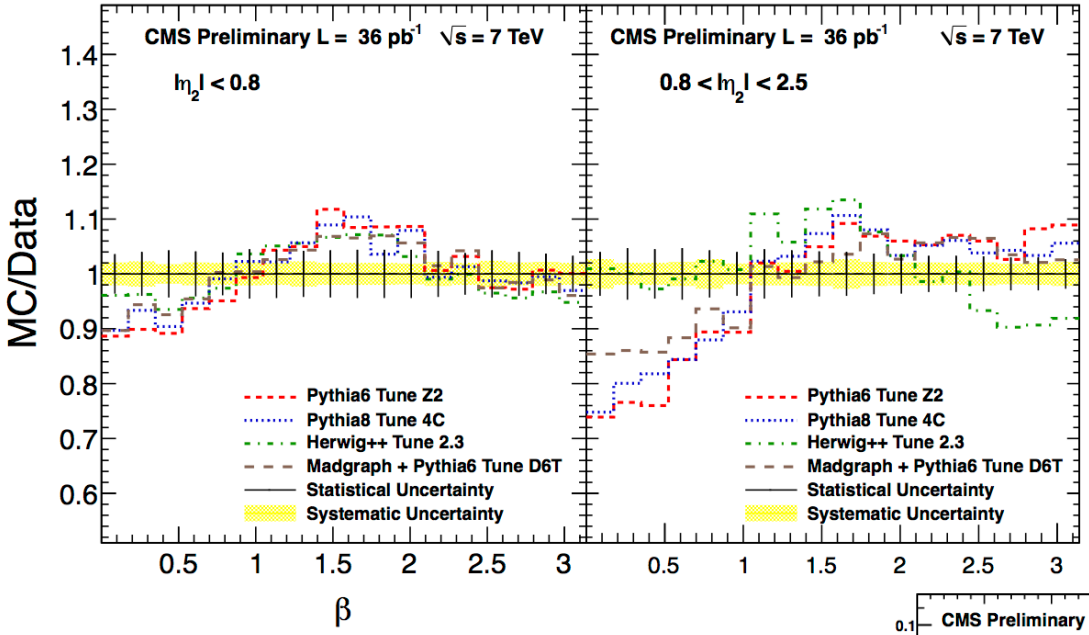
$$\beta = \tan^{-1}\left[\frac{\mathrm{sign}(\eta_2)\Delta\phi_{32}}{\Delta\eta_{32}}\right]$$

β=0: 3rd jet between 2nd & closest proton remnant

β=π: 3rd jet between 2nd & far most proton remnant

- Ideally, e+ e- collider is the best place to do the measurement
  - No color interference from the initial state
- In pp, both initial and final states have color constituents
  - Complicate the signatures
  - Comparison with MC is crucial
- Compare data to event generators with different color coherence implementations

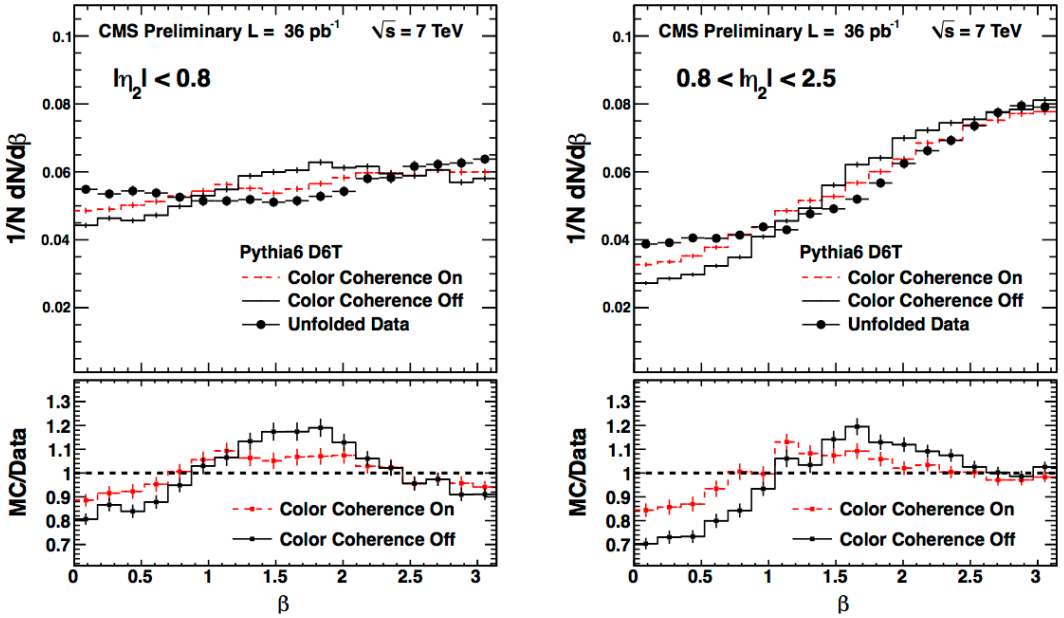
Colour Coherence Results



- Data are unfolded to the particle level
- The data exhibit a clear enhancement of events compared with the PYTHIA and MADGRAPH generators near the event plane (β = 0) and a suppression in the transverse plane (β = π/2)

SMP-12-010

- Comparisons of the β distributions to various MC predictions
  - Herwig++ describes the data β distributions best
- Data clearly support larger color coherence effects in Pythia 6

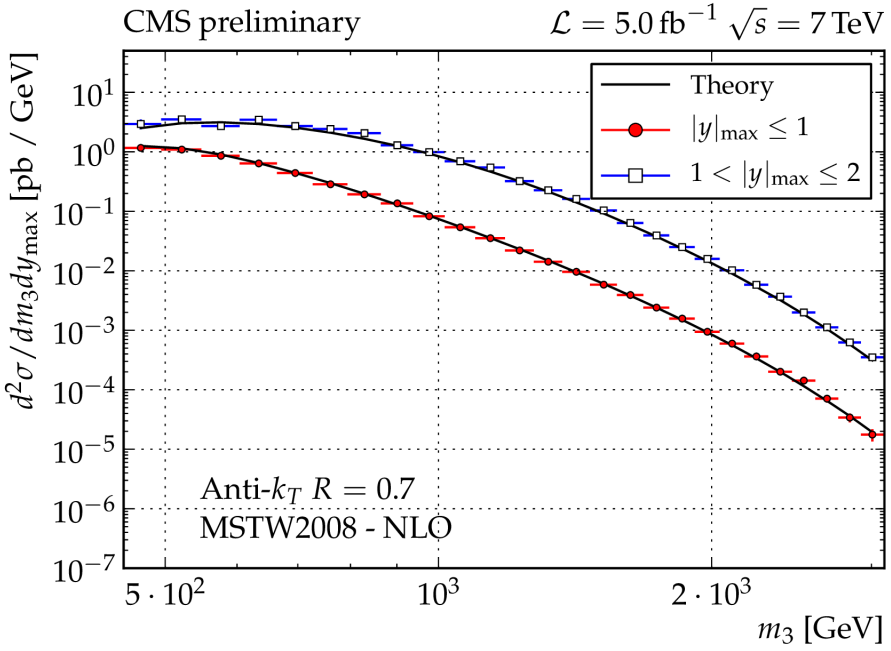


3-Jet Mass Cross Sections @ 7 TeV

Measurement of double diffrential cross section: $d^2\sigma/dm_3dy_{max}$
- sensitivity to PDFs and α_S

❑ $m_3^2 = (p_1+p_2+p_3)^2$ $|y_{max}|=max(|y_1|,|y_2|,|y_3|)$ $Q=m_3/2$

- ❑ Require jet p_T > 100 GeV
- ❑ Regions: $|y_{max}| < 1$ and $1<|y_{max}|<2$ - reach up to $m_3 \sim 3$ TeV
- ❑ Agreement with pQCD @ NLOxNP (*NP correction 8% -> 1%*)
  - Deviations observed with NLO + ABM11 PDFs



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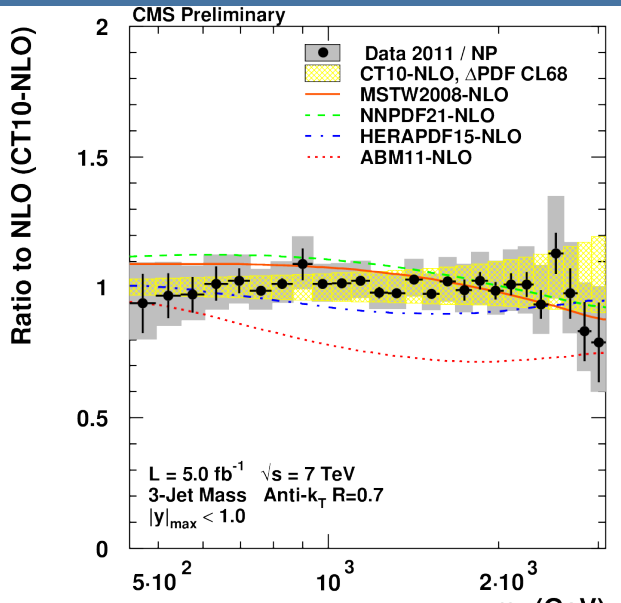

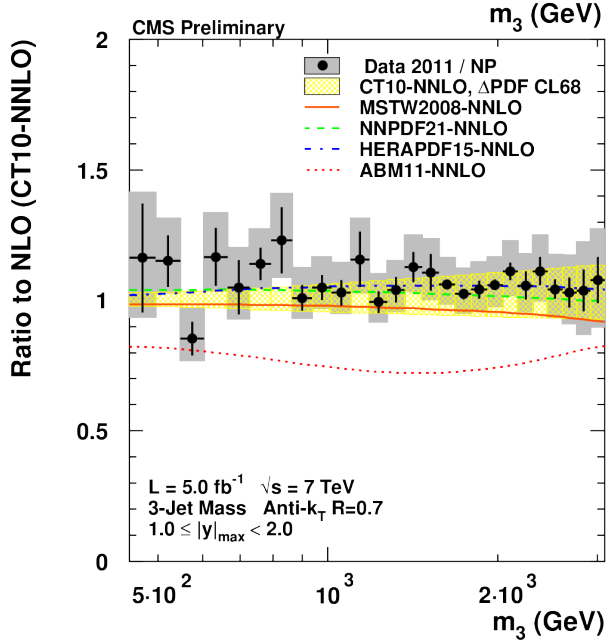

3-jet over 2-jet Cross Section Ratio

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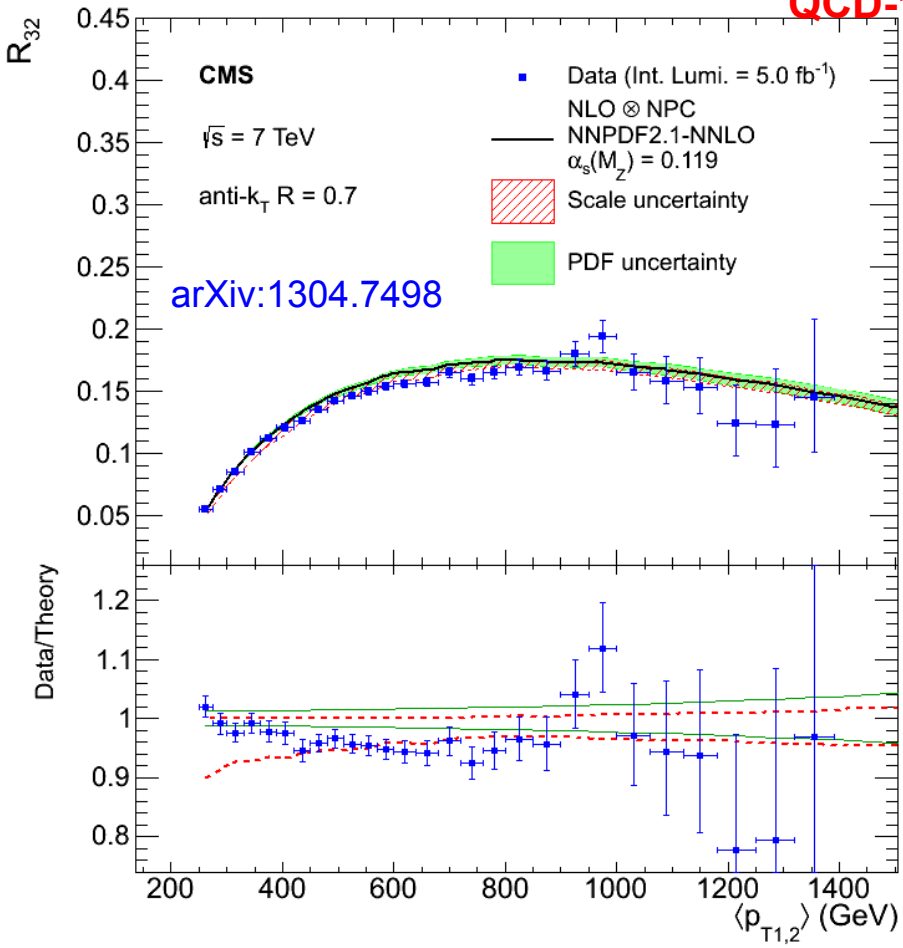
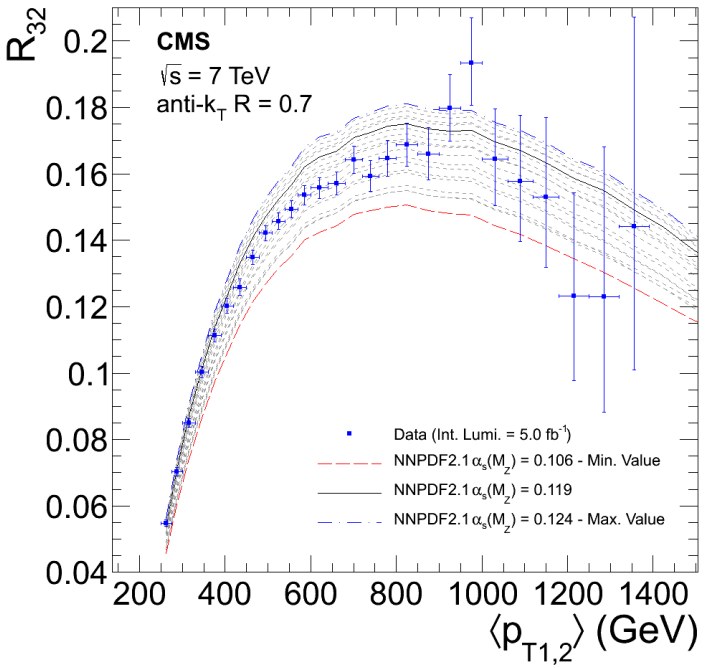
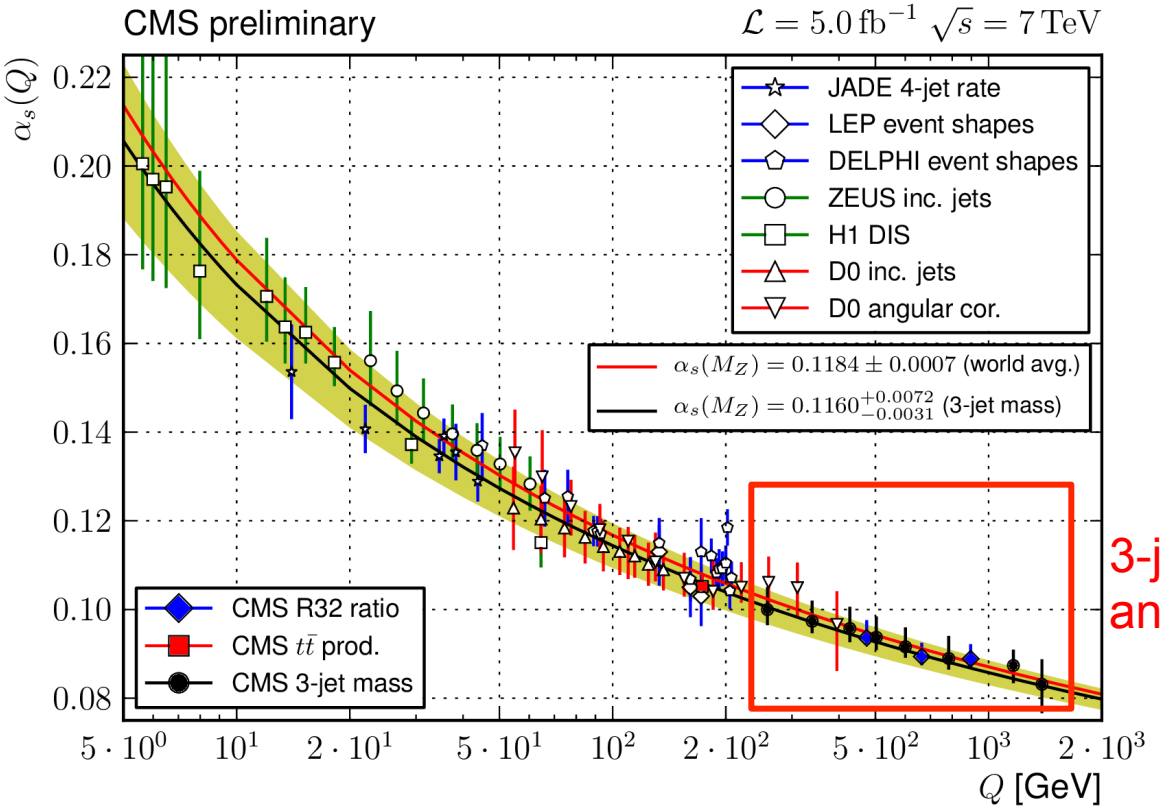




$$R_{32} = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(pp \to n \text{ jets} + X;\ n \geq 3)}{\sigma(pp \to n \text{ jets} + X;\ n \geq 2)} \quad \text{vs} \quad \langle p_{T1,2} \rangle = \frac{p_{T1} + p_{T2}}{2}$$

- Cross section ratio R_{32}:
  - inclusive 3-jet over 2-jet production
  - sensitive to α_S
- Multiple alternative phase-space options
  - depending on the cut imposed on the 3rd jet p_T
  - expressed vs. different observables
  - measuring the α_S: vital to reduce scale uncertainty

Measurement of α_S



SMP-12-027
QCD-11-003
arXiv:1304.7498

3-jet mass and R_{32}

- Extract α_S from the R_{32} and 3-jet mass cross section measurements
  - Results are comparable with world average $\alpha_S(M_z) = 0.1184 \pm 0.0007$
  - For the first time probing the > 1 TeV scale, reaching up to ~ 1.5 TeV
- Dominated by theoretical uncertainties (PDF and scale)

R_{32}: $\alpha_S(M_z) = 0.1148 \pm 0.0014\,(\mathrm{exp.}) \pm 0.0018\,(\mathrm{PDF})^{+0.0050}_{-0.0000}\,(\mathrm{scale})$

3-jet mass: $\alpha_S(M_z) = 0.1160^{+0.0025}_{-0.0023}\,(\mathrm{exp, PDF, NP})^{+0.0068}_{-0.0021}\,(\mathrm{scale})$

Conclusions and Outlook

- Significant ongoing effort to improve our understanding of QCD
  - both experimental and theoretical
  - rich QCD programs pursued LHC
- Large datasets available
  - LHC has provided access to a huge phase space
  - will take a long time to analyze and digest all the data on tape
- Much recent progress
  - jet data have considerable impact on gluon and u/d quark PDFs
  - measurements of α_S at the TeV scale for the first time
- Comments on the theoretical tools
  - in many areas the exp. precision reached makes the NLO predictions insufficient: NNLO needed for further progress!!
  - with some tuning of the parameters, the LO ME or NLO interfaced with PS models provide good description of the data